CONCEPTS FOR FINDING RELOCATABLE TARGETS

SMALL BUSINESS INNOVATIVE RESEARCH TOPIC AF 87-124
PHASE II FINAL REPORT

27 June 1991

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A hybrid (space-based/airborne) bistatic synthetic aperture radar (SAR) concept has been developed at Toyon Research Corporation and a feasibility assessment has been made. The benefits of a sanctuary transmitter architecture to the receive aircraft are 1) high resolution SAR imaging capability at long range from the receive aircraft, day or night, and in all weather; and 2) passive operation, which enables the aircraft to maintain stealth, improve survivability, resist sidelobe jamming, and for some aircraft such as RPVs, drones, etc., take advantage of the weight and prime power savings possible because a transmitter is not required. We show that three Molniya satellites can provide continuous illumination coverage for application to strategic missions, while a single satellite in geostationary orbit is suited to most tactical missions.

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Both low and high altitude satellite systems have been found to offer useful, but different capabilities. Previous experiments have proven the principles and we identify the technologies critical to the development of such a system.

In addition, a brief examination of the concepts for locating mobile missile launchers was performed. This led to a synthesis of a Fast Launch Active Radar Expendable (FLARE) concept. Initial feasibility has been examined.

ABSTRACT

A hybrid (space-based/airborne) bistatic synthetic aperture radar (SAR) concept has been developed at Toyon Research Corporation and a feasibility assessment has been made. The benefits of a sanctuary transmitter architecture to the receive aircraft are 1) high resolution SAR imaging capability at long range from the receive aircraft, day or night, and in all weather; and 2) passive operation, which enables the aircraft to maintain stealth, improve survivability, resist sidelobe jamming, and for some aircraft such as RPVs, drones, etc., take advantage of the weight and prime power savings possible because a transmitter is not required. We show that three Molniya satellites can provide continuous illumination coverage for application to strategic missions, while a single satellite in geostationary orbit is suited to most tactical missions. Both low and high altitude satellite systems have been found to offer useful, but different capabilities. Previous experiments ha⁷⁷ roven the principles and we identify the technologies critical to the development of such a system.

In addition, a brief examination of the concepts for locating mobile missile launchers was performed. This led to a synthesis of a Fast Launch Active Radar Expendable (FLARE) concept. Initial feasibility has been examined.

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PREFACE

As the title of this report suggests, *Toyon Research examined more than one concept for finding relocatable targets.* But, in fact, most of the contract time and money was spent studying a bistatic radar concept. This report deals primarily with the bistatic system. The first chapter provides an overview of the concept, how bistatic fills a niche that other sensor systems cannot, highlights the important results of the analysis, and lists the critical technology areas. The details of the analysis are described in the second and third chapters as well as the appendices. For mostly historical reasons, we have broken the detailed description into two pieces, the first (Chapter 2) dealing with the requirements and capabilities of the bistatic system in the context of a strategic role. The strategic problem is relatively well-defined which leads naturally to a specific preferred architecture, which in turn allows us to focus on the issues unique to the bistatic system, such as resolution versus geometry. In Chapter 3, we broaden (relax) the requirements to the tactical setting and look at the sensitivity of the bistatic system's capability. The appendices contain detailed discussions of the important radar issues and are suited to the audience with a radar background.

The Fast Launch Active Radar Expendable (FLARE) concept is treated as a separate piece of analysis in Chapter 4. The FLARE concept addresses a more narrowly focused problem of finding tactical ballistic missile launchers after they have fired their missiles.

This informal "report" is generally arranged as facing page text to viewgraphs. This format was agreed to by the AF/SSD contract technical monitor in an agreement which stipulated the addition of the FLARE study task near the end of the contract.

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CHAPTER 1
EXECUTIVE SUMMARY

M.P. Grace

PROGRAM HISTORY

This document describes the work performed in Phase II of the overall SBIR effort, however, it is useful to begin by discussing the history of the program and how the concept and topics evolved over time.

The original Phase I topic was an examination of the resistance of a hybrid bistatic radar (HBR) system to ground-based electronic countermeasures (ECM or jamming). We focused on a bistatic concept for space-based moving target indication (MTI) radar. The HBR concept had originally been proposed to AF/SSD by General Dynamics Corporation [1]. The motivation for the Phase I study was to test the claim of ECM invulnerability claimed by the system's proponents.

The HBR concept utilized a satellite transmitter and a passive airborne receiver to perform surveillance. Because conventional retro-directive sidelobe jammers did not know where the receiver was, they were not able to focus their jamming energy on the receiver and hence, were rendered ineffective. Toyon concluded that for nearly all types of jammers considered in Phase I, this geometric dilution of the jammer's energy appeared to work [2]. This was in sharp contrast to the potentially devastating effect of highly directive jammers on monostatic space-based radars, even with deep antenna nulling capability. Perhaps more importantly, Toyon recognized that the bistatic system provided a means for a stealthy aircraft to maintain its low observables while conducting radar surveillance. This idea was synergistic with the concept of using stealthy aircraft to locate and attack strategic relocatable targets.

The focus at the beginning of Phase II then shifted to examining the capability of a hybrid bistatic Synthetic Aperture Radar (SAR) for finding stationary road-mobile missile launchers in the Soviet Union. At first, there were some doubts that typical geometries could provide good imaging capability or that the transmit/receive coordination problem could be solved in the SIOP timeframe without a large number of satellites. However, after study and peer review of the concept as developed, we concluded that the system was (surprisingly) capable in nearly all geometries and that the concept required only three satellites to provide continuous illumination coverage of the Soviet Union. The only problem with the concept was the likelihood of target obscuration, due primarily to trees. While this problem was also faced by monostatic aircraft concepts, the tree obscuration limited the utility of the concept to the situation where the aircraft had small area cues to the target's location.

In the second half of the study, the focus shifted to include the much broader topic of worldwide reconnaissance, especially with tactical applications. The moral of the story, as we will show here, is that a single low earth orbit (LEO) or a repositionable geostationary (GEO) satellite provide useful but very different capabilities.

Finally, near the end of the contract, AF/SSD added a task: a quick look at a concept for aiding a conventional attack aircraft in attacking mobile tactical ballistic missile launchers – the problem of the SCUDs in the Desert Storm battle.

PROGRAM HISTORY

	PHASE I $50k/SIX MONTHS	PHASE II $500k/TWO YEARS	
		SATELLITE/AIRCRAFT BISTATIC SAR	
TOPIC	JAM RESISTANCE OF HYBRID BISTATIC RADAR	STRATEGIC APPLICATIONS → TACTICAL APPLICATIONS	NEW CONCEPT: "FLARE"
MORAL OF THE STORY	ECM RESISTANT, MAINTAINS STEALTH	BISTATIC SYSTEM LOOKS VERY CAPABLE, 1-3 SATELLITES ARE ADEQUATE, TREE OBSCURATION CAN BE A PROBLEM	BOTH LEO AND GEO SATELLITES PROVIDE INTERESTING BUT DIFFERENT CAPABILITIES	THE NEW PROBLEM: SCUDS

SATELLITE ILLUMINATOR

GROUND-BASED
JAMMER

AIRBORNE RECEIVER

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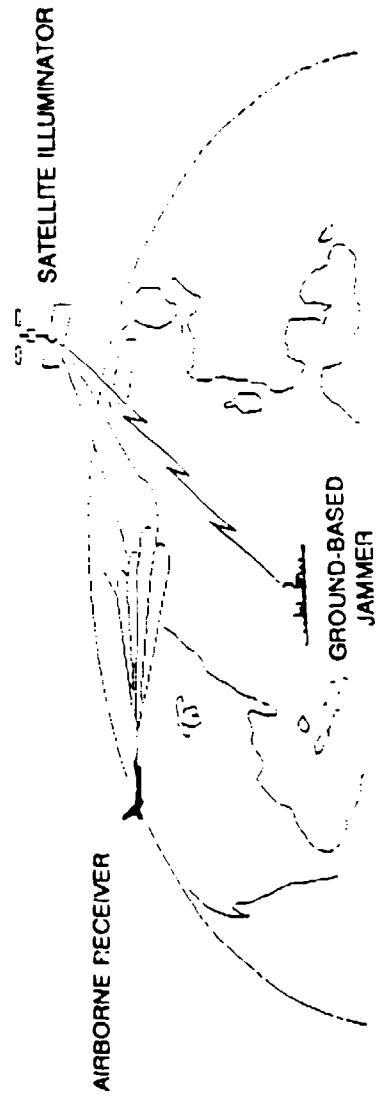
BISTATIC SAR CONCEPT

The chart below illustrates and shows the motivation for the concept. The baseline system uses a satellite radar transmitter (at X-band) to provide floodlight illumination of a large spot on the ground. We will consider the specific spot size later, but for now assume that the spot is big enough (approximately 400 km across) that multiple receive aircraft fly over the spot and perform independent SAR mapping missions. The satellite may orbit the Earth at low altitude (1000 km) or at geosynchronous altitude (44,000 km). In both cases, the spot size is the same, with the higher altitude satellite employing a correspondingly larger antenna to confine the illumination to the fixed spot size. The moving Low Earth Orbit (LEO) satellite is assumed to steer its antenna beam to maintain the illuminated spot fixed on the ground.

The benefits to the receive aircraft in this system are:

1) High resolution SAR imaging capability at long range from the receive aircraft, day or night, and in all weather.

2) Passive operation, which enables the aircraft to maintain stealth, if so equipped, resist sidelobe jamming, and for some aircraft such as RPVs, drones, etc., take advantage of the weight and prime power savings possible because a transmitter is not required.

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BISTATIC SAR CONCEPT

ILLUMINATOR SATELLITE IN LEO OR GEO
FLOODS SPOT ON GROUND

PRIMARY MOTIVATION:

- RETAIN RADAR SENSOR ADVANTAGES
  - ALL-WEATHER, LONG-RANGE, HI-RES

- PASSIVE RECEIVER
  - MAINTAIN LOW OBSERVABLES
  - RESISTANT TO SIDELOBE ECM
  - POWER/WEIGHT OF TRANSMITTER
    NOT REQUIRED
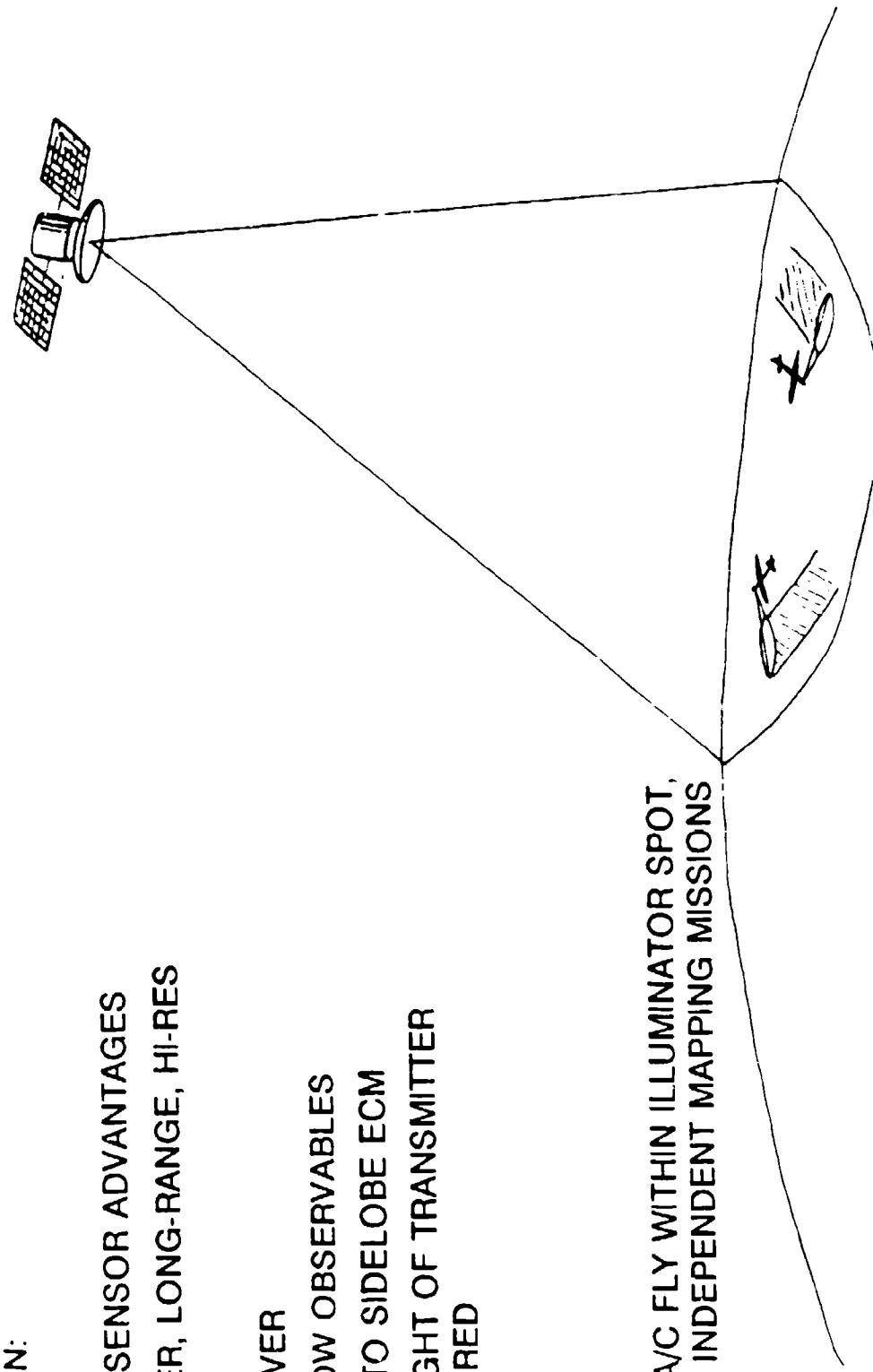
RECEIVE A/C FLY WITHIN ILLUMINATOR SPOT,
PERFORM INDEPENDENT MAPPING MISSIONS

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WHERE BISTATIC FITS

It is important to keep in mind how our bistatic system contrasts with monostatic alternatives. The chart below illustrates the main advantages and disadvantages of the various systems. First consider the monostatic satellite. While orbiting high above the Earth, it provides worldwide coverage, but the long range associated with satellite altitudes requires the highest power relative to the other systems and is vulnerable to sidelobe jamming, despite antenna nulling. In order to minimize the required power, the monostatic SAR satellite is usually driven to low earth orbit, yielding limited temporal coverage on each pass, and only two passes per day over any given spot.

The bistatic concept can, in theory, use much less power than the monostatic satellite since the receive leg of the transmission path is generally much shorter. Yet to take advantage of this potential savings requires a high degree of coordination of transmit/receive beam footprints on the ground. Generally, the means of alleviating this coordination problem involves accepting a penalty of increased transmit power as we will show later. Finally, because the transmit and receive platforms are separate, the unobscured target viewing geometries are generally more restrictive than either of the monostatic alternatives.

Of the three possibilities, the monostatic aircraft requires the least power, is the simplest and least expensive, and the coverage can be tailored to virtually any mission requirement. However, as compared with the passive bistatic receiver, the monostatic aircraft is vulnerable to attack, either physically or electronically. Thus, the bistatic system fills a niche between monostatic satellites and aircraft. We will see that the problem of increased complexity appears solvable and that the imaging capability of the system is excellent.

WHERE BISTATIC FITS

MONOSTATIC AIRCRAFT	BISTATIC	MONOSTATIC SATELLITE
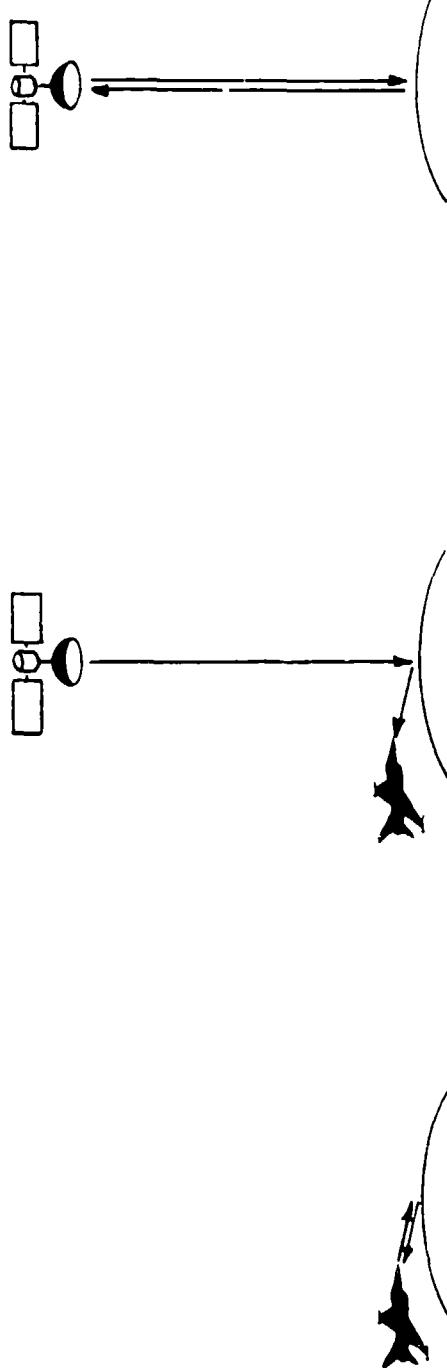
PROS:

Simplest, Lowest Power, Most Flexible Coverage	Passive Aircraft, Potentially Less Power Than Mono Satellite	Worldwide Coverage, Peacetime Overflight

CONS:

Easily Intercepted, Susceptible to Jamming	High Complexity, Added Visibility Constraints	Highest Power, Limited Temporal Coverage, Easily Jammed

STUDY ACCOMPLISHMENTS

This chart lists the major topics covered over the course of the Phase II contract. The effort was aimed at answering the critical question: can the bistatic SAR system work? We purposely ignored some important operational issues. As an example, we were more concerned with the bistatic image formation process than the issue of how the imagery could be used to find and attack targets. A second goal was to identify how the system could be configured for various missions.

We will only discuss some of the highlights from the analysis in this chapter, and leave the bulk of the results for the later chapters.

STUDY ACCOMPLISHMENTS

RADAR SYSTEMS ANALYSIS:

- STUDIED SAR RESOLUTION AND COVERAGE RATE AS A FUNCTION OF GEOMETRY

  - DEVELOPED NEW METHODOLOGY[†]

  - SENSITIVITY TO AIRCRAFT SPEED & ALTITUDE, SATELLITE ORBIT

- SIZED BISTATIC SYSTEM

- CALCULATED BENEFITS OF PASSIVE RECEIVER

  - DETECTABILITY OF MONOSTATIC "LPI" SAR

  - JAMMING AGAINST INVISIBLE BISTATIC SAR RECEIVER

- IDENTIFIED CRITICAL TECHNOLOGIES

OPERATIONS ANALYSIS:

- SYNTHESIZED SATELLITE CONSTELLATIONS

  - SRT MISSION: 3 MOLNIYA

  - TACTICAL MISSION: 1 IN LEO OR GEO

- "BALLPARKED" DESIGN REQUIREMENTS FROM TARGET CHARACTERISTICS

[†]G.P. Cardillo, *On the Use of the Gradient to Determine Bistatic SAR Resolution*, 18 December 1989, TD 5-127, Toyon Research Corporation.

EXAMPLE: IMPACT OF SATELLITE ALTITUDE ON RESOLUTION

One of the unknowns at the beginning of this effort was how bistatic SAR resolution varied with the imaging geometry. In order to examine this, Toyon developed a gradient-based resolution prediction computer code. Shown below are example outputs from the program – ground maps indicating regions of acceptable resolution capability (in this case < 1 meter in both down-range and cross-range) for two satellite geometries. In both cases, the bistatic receive aircraft is located 10 km above the center of the map flying up the page. The case on the left corresponds to a geostationary satellite located to the right of the map such that the transmit grazing angle is 45 degrees. The case on the right corresponds to a 1000 km altitude satellite, again positioned to the right of the map at a 45 degree transmit grazing angle. The velocity vector of the LEO satellite is oriented relative to the map as shown by the arrow through the satellite icon.

These two geometries point out an important difference between GEO and LEO orbits in terms of resolution capability. The GEO case (left) indicates acceptable resolution out to the aircraft's horizon. The LEO case (right) indicates good resolution out to 70 km from the aircraft. In general, the LEO system has better long range resolution performance for a fixed bandwidth and coherent integration time (500 MHz and 10 s, respectively, in this case). This results because the motion of the system is dominated by the satellite, creating a longer aperture in the fixed integration time. The integration time is limited to about 30 s or less by oscillator stability, motion sensing equipment, and the antenna vibration environment. The particular example on the right also points out an interesting capability unique to bistatic systems, the ability to image directly in front of the receiver. This capability is not possible with the GEO configuration.

The apparent advantage of the LEO system may be canceled out by the lack of sensitivity to see targets at the longer range or by the requirement to reject ambiguous range returns. It must also be pointed out that the superior performance of the LEO system is achieved only over a very limited range of geometries. In the case of the GEO illuminator, the motion that creates the synthetic aperture is due solely to the aircraft. For this reason, the long-range performance of the GEO system is very insensitive to satellite/aircraft relative geometry. Higher speed aircraft result in better resolution. GEO also eases the transmit/receive coordination problem. For these reasons, and because it can provide continuous illumination coverage of a tactical theater with a single satellite, GEO is probably the preferred configuration.

EXAMPLE: IMPACT OF SATELLITE ALTITUDE ON RESOLUTION

1000 km ALTITUDE SATELLITE
45° TRANSMIT GRAZING ANGLE
10 km ALTITUDE A/C, 200 m/s

< 1 m RESOLUTION

> 1 m RESOLUTION

km

-400   0   400

GEOSTATIONARY ALTITUDE SATELLITE
45° TRANSMIT GRAZING ANGLE
10 km ALTITUDE A/C, 200 m/s

< 1 m RESOLUTION

> 1 m RESOLUTION

km

-400   0   400
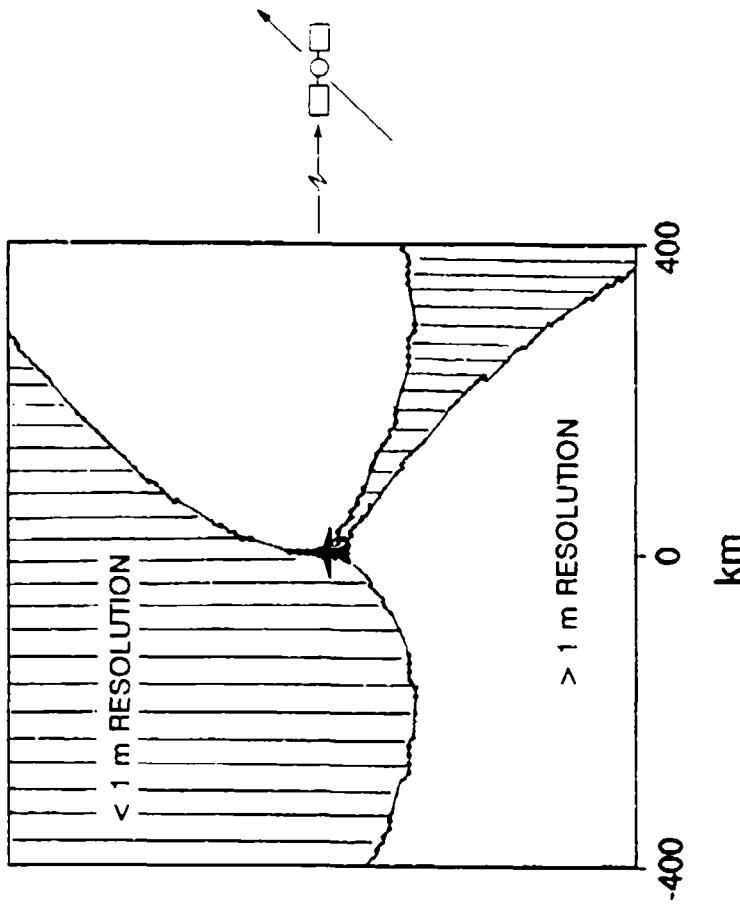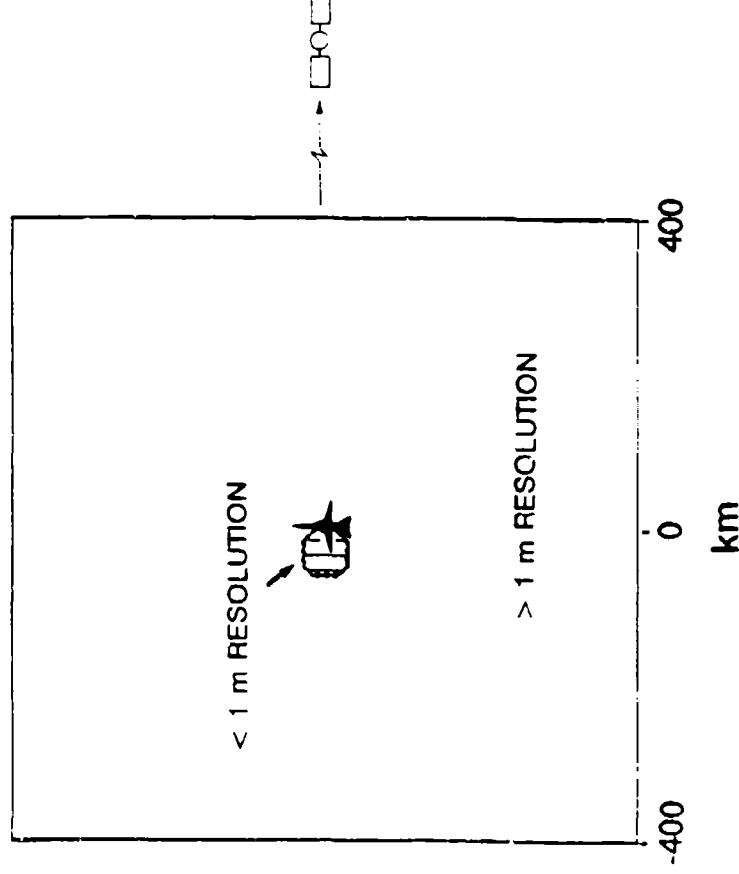
SATELLITE ALTITUDE TRADE-OFFS

As we have indicated, both LEO and GEO illuminator systems can deliver excellent long-range imaging performance. The chart below summarizes the important differences between these possibilities[1].

Monostatic aircraft radars could be modified to function as bistatic receivers. If this could be done cost effectively, then the major cost associated with the bistatic system would be due to the satellite. It is also possible to use a next generation monostatic space-based radar (SBR) (assuming the SBR will be deployed) as an illuminator for the bistatic system, resulting in the lowest cost bistatic implementation. But, because a monostatic satellite radar design is driven to LEO, this approach suffers from limited temporal coverage from a single satellite, albeit worldwide.

A GEO system would offer continuous coverage, but only over a particular region of the Earth, and without polar coverage. However, geostationary satellites can be repositioned over theaters of interest within a few weeks to a few months, depending on the amount of propellant carried by the satellite. Of course, a GEO system is not capable of monostatic SAR imaging, but may be useful for limited MTI surveillance.

It should be noted that power required by the transmitter is independent of satellite altitude, but is instead a function of spot size on the ground as we show next.

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[1]A third possibility, appropriate for the strategic role, utilizes highly elliptical Molniya orbits to give continuous coverage of the Soviet Union at steep grazing angles with three satellites. The Molniya illuminator transmits while near its apogee, slightly higher than geostationary altitude. Thus, from an image formation standpoint, the Molniya case is nearly identical to the GEO case.

SATELLITE ALTITUDE TRADE-OFFS

- LOW EARTH ORBIT

  - POTENTIALLY LOW COST IF PIGGYBACKED ON NEXT GENERATION MONOSTATIC SBR (USEFUL IF MONOSTATIC IS JAMMED)

  - WORLDWIDE SPATIAL COVERAGE

  - LIMITED TEMPORAL COVERAGE (< 10 MIN. PER PASS)

  - MONOSTATIC FAVORS LEO

- GEOSTATIONARY (OR MOLNIYA FOR SRT MISSION)

  - CONTINUOUS (8 HR MOLNIYA) COVERAGE

  - CAN BE REPOSITIONED, RESPONSE TIME VS. PROPELLANT WEIGHT

- POWER DEPENDS ON SPOT SIZE, NOT ALTITUDE

TRANSMITTER POWER REQUIREMENT

The radar power required does not depend on satellite altitude. This can be explained by the fact that the receiver requires a certain power density on the ground to image at its design range. Since the total area on the ground is fixed (by assumption), the total power is fixed. Note that in this case, the transmit aperture must be proportionately larger at higher altitude to focus the power on the spot. The graph below shows power requirement as a function of spot size.

TRANSMITTER POWER REQUIREMENT

SATELLITE AT ALTITUDE H

$\bar{P} \propto \theta_T^2 R_T^2 \approx d^2$

$\theta_T \approx \dfrac{d}{H}$

$R_T \approx H$

$$\bar{P} = \frac{(S/N)\, d^2\, \pi^2\, R_2^2\, kTBFL}{\sigma A_r}$$

PARAMETERS

S/N = 17 dB
σ = 1 m²
R_2 = 70 km
B = 0.1 Hz
F = 4 dB
L = 10 dB
A_r = 1 m²

AVERAGE RADIATED POWER, WATTS

SPOT DIAMETER, km
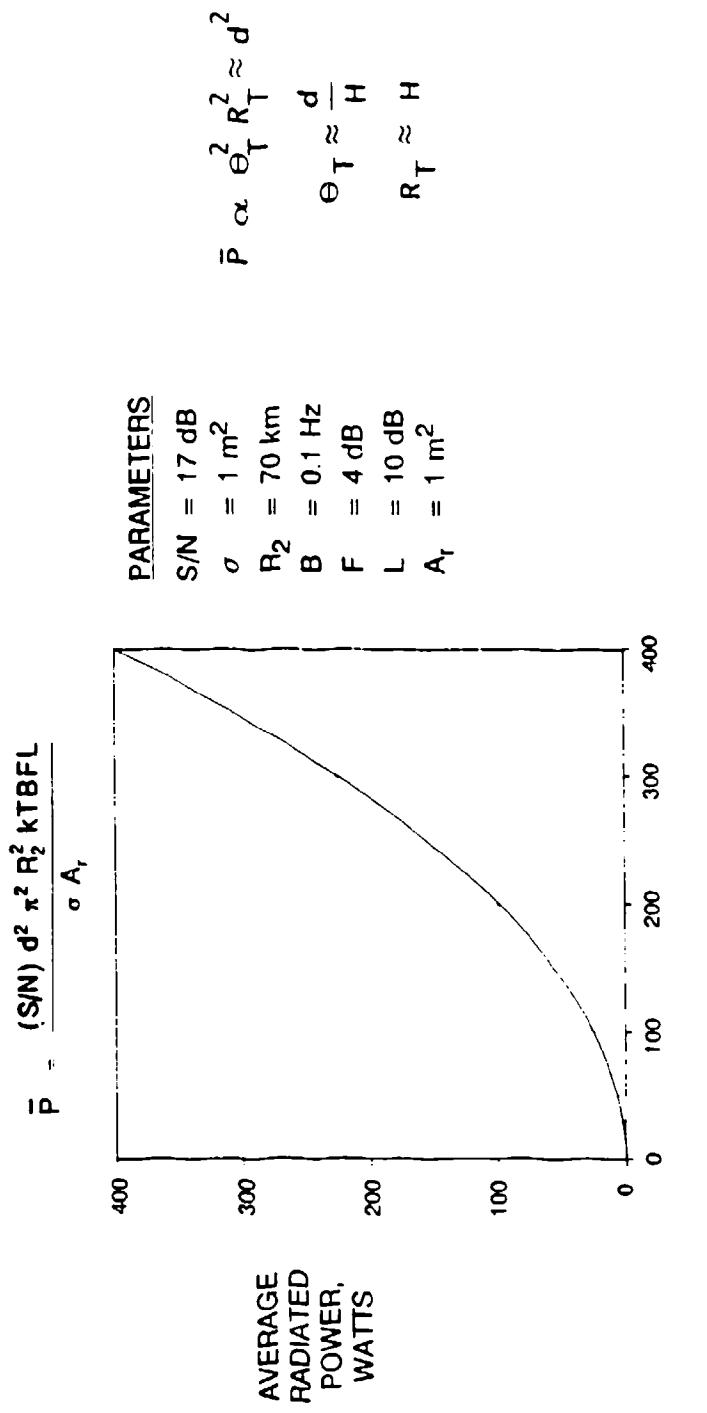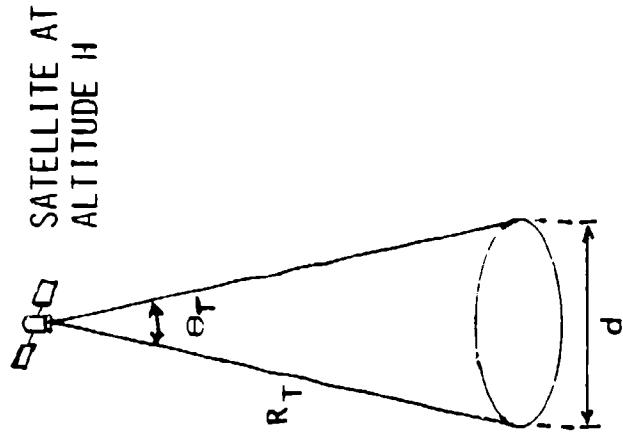
CRITICAL TECHNOLOGIES

The chart below summarizes those technologies thought to be critical to the feasibility of the bistatic system. For systems which use a large spot size to ease the coordination problem or to gain wide-area coverage via multiple receive platforms, the transmitter power required may be an issue, particularly if there is a requirement to see very small radar-cross-section targets. Also illumination may have to be provided during satellite eclipse (assuming solar power source) which creates an energy storage problem. The power requirements can be eased by going to a smaller spot size, but then the beam agility required to follow the receive beam probably forces the antenna to use a phased array design. For geostationary orbits, the resulting large array size required could be prohibitive.

The bistatic image formation algorithm is inherently more complex than monostatic, requiring accurate position information of both platforms relative to the target. Two techniques have been identified as possible ways to solve this geometry problem, but a preferred approach has not been found. This remains an issue with the system concept and is treated further in the appendix.

While transmit antenna sidelobe control is generally not an issue with the bistatic system (particularly with large illumination spot sizes), the burden of rejecting azimuth ambiguities is shifted to the receive sidelobes only, creating a sidelobe level requirement more stressing than that of a monostatic aircraft SAR. The requirements are derived in the appendix and appear achievable.

While there are several technology areas critical to this concept, we have been encouraged by the successful demonstration of high resolution (1 m) bistatic SAR using two aircraft as well as demonstration of space-based/aircraft bistatic SAR using the Shuttle Imaging Radar as the transmitter. We have consulted the experts in these systems and they have found no fundamental flaws with the bistatic system described herein and have expressed optimism that such a system could be built.

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CRITICAL TECHNOLOGIES

- TRANSMITTER POWER SOURCE AND ENERGY STORAGE (LARGE SPOT)

- LARGE ILLUMINATOR PHASED ARRAY (SMALL SPOT)

- GRIDLOCK AND MOTION COMPENSATION

- RECEIVER SIDELOBE CONTROL

- PRINCIPLES HAVE BEEN DEMONSTRATED
  - TBIRD DEMONSTRATED HI-RES BISTATIC SAR
  - SIR-B,C DEMONSTRATED HYBRID BISTATIC SAR

CONCLUSIONS

The chart below lists the conclusions from our Phase II activity. The hybrid bistatic SAR concept appears attractive for a passive, all-weather tactical strike, reconnaissance, or strategic bomber aircraft. The recent Persian Gulf war demonstrated the need for these capabilities, but no existing single aircraft appears capable of passive, all-weather imaging as the bistatic system is.

While the system has useful capabilities using either low-Earth or geosynchronous orbit, the lowest cost imple-ineration would rely on a next generation monostatic satellite to provide illumination. By lowest cost, we mean the inc. man tal cost to modify the satellite to perform as a bistatic illuminator in an adjunct mode would probably be much less than a dedicated bistatic illuminator.

If the benefits of a bistatic system were judged to warrant the expense of a dedicated bistatic satellite, the preferred architecture would employ high altitude satellites. A single repositionable geostationary illuminator would be adequate for most tactical scenarios where there was time to move the satellite into position. Unfortunately, such a satellite would not be appropriate for monostatic SAR. It might be able to provide MTi coverage, although the power-aperture requirements would be much higher than that required for bistatic illumination.

Based on the experiments performed to date, and our preliminary assessment of the system requirements, Toyon feels that a useful hybrid bistatic SAR system is feasible with today's technology.

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CONCLUSIONS

- CONCEPT SUPPORTS ATTRACTIVE FOR PASSIVE, ALL-WEATHER TACTICAL STRIKE, RECCE, AND STRATEGIC BOMBER AIRCRAFT

- LOWEST COST IMPLEMENTATION PIGGYBACKS ON NEXT GENERATION SBR (LEO)

  - ADVANTAGEOUS IF SBR IS JAMMED, OR LACKS SUFFICIENT SENSITIVITY
  - WORLDWIDE SPATIAL COVERAGE
  - LIMITED TEMPORAL COVERAGE

- DEDICATED (GEO OR MOLNIYA) SATELLITE OFFERS TEMPORAL FLEXIBILITY

  - REQUIRES 1-3 SATELLITES FOR CONTINUOUS COVERAGE
  - FOR SINGLE SAT: SPATIAL RESPONSIVENESS VS. EXCESS FUEL WEIGHT

- CONCEPT AND CRITICAL TECHNOLOGIES HAVE BEEN DEMONSTRATED

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RECOMMENDATIONS ON BISTATIC SAR

From a positive theoretical assessment of the concept feasibility comes the logical question: Where do we go from here? The chart below outlines our recommendations for a possible follow-on effort to take the concept away from theory towards a practical system architecture. To begin with, we feel that should AF/SSD begin to develop a new space-based SAR platform, then bistatic illumination should be considered as an adjunct mode of operation in the design. It may be possible to add this capability to a monostatic system design at minimal cost (part of a requirements analysis task described below).

With the general goal of furthering development of our bistatic SAR concept, we have outlined the necessary tasks aimed at 1) quantifying the benefit of such a system to potential users; 2) analyzing requirements of the system components and their integration; and 3) assisting AF/SSD in program planning. Some of the key issues/questions to be addressed are listed below.

RECOMMENDATIONS ON BISTATIC SAR

- BISTATIC ADJUNCT MODE SHOULD BE CONSIDERED IN THE DEVELOPMENT OF ANY NEW SPACE-BASED SAR PLATFORM

- TASKS FOR POSSIBLE FOLLOW-ON:

  - QUANTIFY BENEFITS OF PASSIVE SAR
    - EXISTING SIMULATION AVAILABLE
    - COMPARE TO MONOSTATIC ALTERNATIVES
    - VULNERABILITY ASSESSMENT
    - CONSIDER LO & CONVENTIONAL RECEIVE PLATFORMS

  - REQUIREMENTS ANALYSIS
    - SATELLITE
      - POWER, APERTURE
      - S/I RATIO, RESOLUTION REQUIREMENTS
      - PIGGYBACK VS. DEDICATED

    - AIRCRAFT
      - IDENTIFY CANDIDATES (F-15, B-2, F-117, HALE?)
      - MODIFICATIONS FOR BISTATIC OPERATION

    - SATELLITE/AIRCRAFT COORDINATION
      - DECREASED TX POWER VS. INCREASED COMPLEXITY OF T/R COORDINATION
      - PREFERRED APPROACH TO GRIDLOCK, MOTION COMPENSATION

  - PROGRAM PLANNING
    - INDUSTRY DESIGN STUDIES
    - CRITICAL EXPERIMENTS
    - SYSTEM DESIGN

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CHAPTER 2
STRATEGIC APPLICATIONS

M.P. Grace

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SPACE-BASED/AIRBORNE BISTATIC SAR FOR FINDING
STRATEGIC RELOCATABLE TARGETS

We begin by briefly describing the nature of the strategic relocatable target (SRT) problem and how it sets the requirements and defines the figures of merit of a bistatic imaging radar system for finding these targets. The concept description begins with a short discussion of the trade-off between target visibility and required search time. We then summarize the detailed system requirements analyses and present a strawman design. There were numerous observations which led us to our strawman design and we reiterate these at the end of this chapter.

S/A BISTATIC SAR CONCEPT

The satellite serves as a transmitter to illuminate the ground while an aircraft passively receives reflected RF energy. By applying extensions of the conventional algorithms, the receiver forms a bistatic synthetic aperture radar (SAR) map of a region within the area illuminated by the satellite. As the aircraft flies along, this imaging process sweeps out a map swath in which SRTs hopefully can be detected.

S/A BISTATIC SAR CONCEPT

- OBJECTIVE: DETERMINE LIMITS OF A HI-RES IMAGING BISTATIC RADAR
  TO SEARCH REGIONS OF THE SOVIET UNION FOR SRTs

- EMPHASIZE UNIQUELY BISTATIC ISSUES

SATELLITE ILLUMINATOR FLOODS AREA ON GROUND
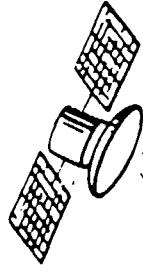
RECEIVER ON BOMBER PASSIVELY MAPS OUT (SAR) SWATH
WITHIN FLOOD-LIT AREA TO LOCATE SRTs

IMAGED SWATH
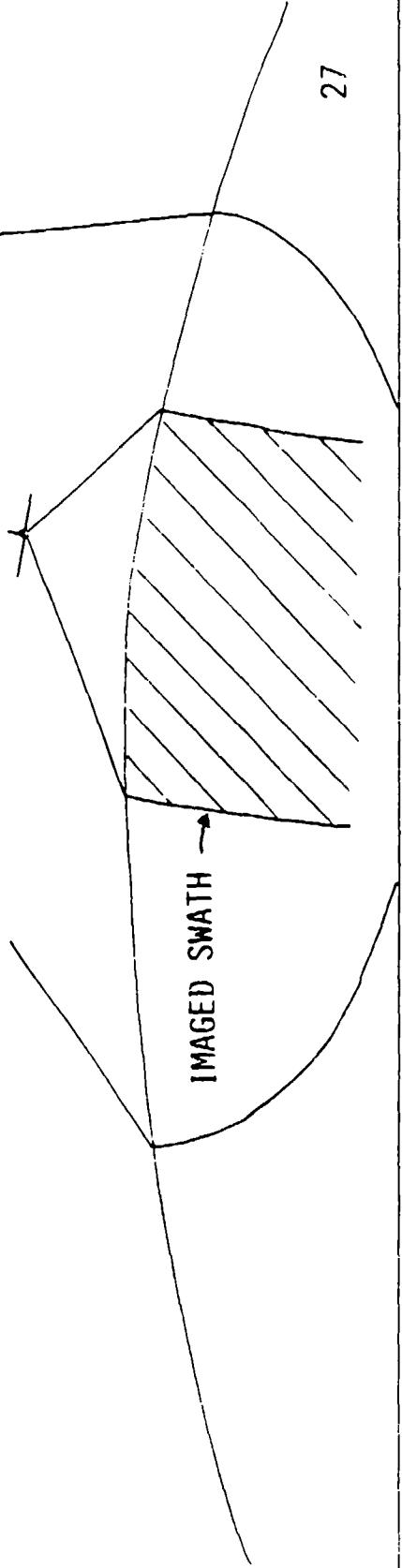
BENEFITS OF BISTATIC OPERATION

This chart lists the reasons for studying this type of bistatic concept. First and foremost, the receive platform need not radiate and therefore can be more survivable. Of course, the degree to which survivability is enhanced depends on many factors including the capability of the air-defense network, the receive platform's passive signature, and operational considerations such as the platform altitude.

Additionally, the bistatic system is inherently resistant to retro-directive jamming as was well documented in the Phase I study. SAR operation also helps in this regard because typically a SAR uses waveforms which have a "spread-spectrum" character.

The range along the receive path from the target to the aircraft is typically a hundred kilometers vs. the satellite's transmit path of over a thousand kilometers. Because of this, the transmit power requirements may be reduced by as much as two orders of magnitude over that required by a monostatic space-based SAR.

Some monostatic satellite concepts must rely on ground stations either for image formation, image processing, or target information distribution. In the SIOP time-frame, the survivability of these ground stations is very difficult to ensure. Another benefit to this bistatic concept is that the image processing is distributed over the surviving aircraft, presumably the same vehicles which must attack the targets.

Lastly, because the receive platform does not need a transmitter, significant prime power and weight savings may be realized. While this savings might not be realized on a bomber aircraft due to the need to operate monostatically as well, it does seem desirable for special purpose vehicles such as drones, RPVs, and high-altitude/long-endurance vehicles.

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BENEFITS OF BISTATIC OPERATION

- SILENT BOMBER HAS ENHANCED SURVIVABILITY

- RESISTANCE TO RETRO-DIRECTIVE ECM

- REDUCED POWER REQUIREMENTS OVER MONOSTATIC SATELLITE $(R_2 << R_1)$

- RECEIVERS & PROCESSING DISTRIBUTED ON SURVIVING A/C

- TRANSMITTER (POWER, WEIGHT) NOT REQUIRED ON RECEIVE PLATFORM

BISTATIC TECHNOLOGY DEMONSTRATIONS

We have been encouraged in our study of this concept by learning of several bistatic SAR demonstration programs. This chart summarizes those programs we know about. Under this contract we have visited with LORAL Corporation in Litchfield Park, AZ where we saw examples of high quality, high-resolution imagery generated using two aircraft as transmitter and receiver.

More recently, we have seen examples of bistatic SAR imagery taken using the space shuttle's SIR-B radar as a transmitter and a JPL testbed aircraft as a receiver. It is also our understanding that a similar test is also planned using the SIR-C radar. These tests do not demonstrate the very high resolution achieved by monostatic aircraft and satellite systems at long range. Nevertheless, these test programs support our belief that the technical problems of bistatic SAR imaging using a space-based transmitter and airborne receiver (i.e., motion compensation) are solvable with present or near-future technology.

BISTATIC SAR TECHNOLOGY DEMONSTRATIONS

- GOODYFAR/LORAL TBIRD AND BTT PROGRAMS (1984)
  - USED "TETHERED AIRCRAFT", LARGE BISTATIC ANGLES (130 DEG.)
  - X-BAND IMAGERY. 2-3 M. RESOLUTION
  - SYNCHRONIZATION VIA ATOMIC CLOCKS
  - OBSERVED REDUCED IMAGE SPECKLE OVER MONOSTATIC

- SIR-B
  - USED TRANSMITTER ON SHUTTLE, RECEIVER ON JPL TESTBED ACFT.
  - L-BAND, 20 M. RESOLUTION
  - SYNCHRONIZATION VIA DIRECT PATH RECEPTION

- SIR-C (RESULTS NOT AVAILABLE YET)
  - L-, C-, & POSSIBLY X-BAND, 6-10 M RESOLUTION
  - WIDER DYNAMIC RANGE THAN SIR-B

CLASS OF SRTs TO BE CONSIDERED: LAND-MOBILE MISSILES

This chart and the next describe the nature of the targets, the problem of finding them, how this impacts system requirements, and the relevant figures of merit. The problem is to detect Soviet land-mobile missiles, either the rail- or road-mobile type. But within this target class, the nature of the search can be quite different for the two target types. As can be seen from the top figure, the rail-mobile missiles (designated SS-24) lend themselves to a linear type of search process but this could still lead to flying over or illuminating the entire Soviet Union. On the other hand, the road-mobile missiles (SS-25) are assumed to disperse over an area surrounding their operating base but are capable of going practically anywhere within their dispersal region.

At the outset, we were hopeful that our concept might lead to a solution to the wide-area search problem for SS-25s. Other efforts at Toyon have led us to believe that the problem of finding SS-24s is more amenable to conventional sensors on airborne platforms [3]. For these reasons, we have focused on the SS-25 problem.

CLASS OF SRTs TO BE CONSIDERED: LAND-MOBILE MISSILES
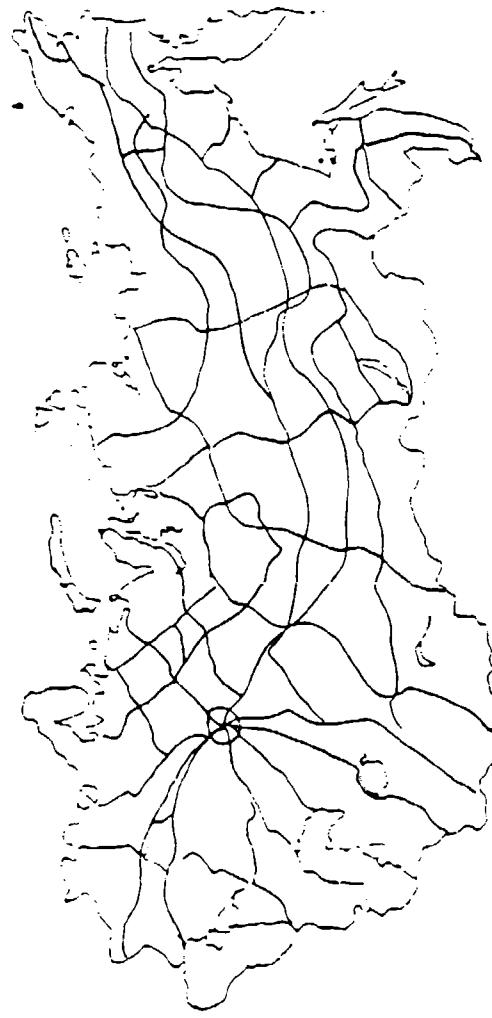
SS-24s
RAIL MOBILE

NOTIONAL SOVIET RAIL NETWORK

- PILOT STUDY FOCUS:
  SS-25s
  ROAD MOBILE

NOTIONAL SS-25 DISPERSAL REGIONS

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ASSUMED TARGET DEPLOYMENT & SEARCH STRATEGY

As mentioned previously, the SS-25s are assumed to be deployed out of a main operating base (MOB). During peacetime, they spend some of the time parked in the MOB and the rest of the time out on training and readiness missions in a area roughly centered on the MOB. However, in the event of crisis or war, it seems certain that the '25s will disperse within the surrounding region to war-time locations.

They may move to avoid being seen or to "hunker down" in the trees and hide. But they need to maintain some level of launch readiness to be useful to the Soviet command structure as a weapon system. They must also be tied in with the Soviet command and know their position and orientation accurately for targeting purposes. It may be the case when they move to a location, they phone or radio to inform the command of their status and get a position fix. However, such an assumption is optimistic. It seems reasonable that the SS-25s could stop at any one of a huge number of possible pre-surveyed sites on a regular schedule or command that required minimal or no messages be sent out. The Soviet equivalent of GPS might also be used to get a position fix.

Regardless of what the Soviets do with the SS-25s, three types of possible search strategies emerge. The easiest (from the sensor point of view) is only having to search the MOB itself or perhaps a limited number of known hiding spots. A more difficult job would be to have to search a local areas surrounding the last reported locations. The most difficult scenario would be if there were no a-priori information about the target's location and the entire dispersal region had to be searched. The progression described roughly requires two orders of magnitude increase in search capability at each step. We would like to know which of these possible search strategies is within the bistatic SAR's capability.

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ASSUMED TARGET DEPLOYMENT & SEARCH STRATEGY

- SS-25s DEPLOYED FROM MAIN OPERATING BASE (MOB)

  - PEACETIME: FRACTION ON TRAINING EXERCISES. READINESS MISSIONS

  - CRISIS: DISPERSE WITHIN REGION SURROUNDING MOB
    REGULAR MOVE-HIDE CYCLE, FAVOR CONCEALED LOCATIONS (TREES),
    C3: PRE-SURVEYED SITES, MINIMIZE EMISSIONS

- POSSIBLE SEARCH STRATEGIES:

  - MOB, SITE OCCUPANCY CHECK (< 1 SQ.KM.)

  - SIGINT-CUED AREA SEARCH (APPROX. 100 SQ.KM.)

  - WIDE-AREA SEARCH (10'S THOUSAND SQ.KM. PER MOB)

- DETERMINE STRATEGIES WITHIN BISTATIC SAR'S CAPABILITY

SS-25 DIMENSIONS AND SENSOR IMPACTS

The main reason for considering a radar sensor for detecting SRTs is the desire to have all-weather capability at high altitude (i.e., long range) where wide-area coverage is possible. Unfortunately, the radar signature from the stationary SRT cannot be discriminated from the background clutter except by SAR imaging.

In order to recognize a pattern of target scattering centers within the cluttered background, the radar must be capable of resolving target scatterers. The figure opposite shows the dimensions of a Soviet launcher adaptable to the SS-25. Judging from the picture, it seems that roughly 1 meter resolution would be adequate to separate unique features of the target such as the wheels. It may be that higher resolution is required since the visual signature may be quite different from the radar signature. For this study, we have assumed 1 meter resolution in both dimensions as a minimum requirement. Further, in order for the scattering centers to be recognizable, we assumed a minimum 10 dB signal-to-noise ratio on a representative 1 m**2 rcs scatterer. We cannot comment on the detectability of SRTs imaged under these conditions (especially using auto-target recognition or ATR systems), but we have examined the sensitivity of the concept and the strawman design to these assumptions.

SS-25 DIMENSIONS AND SENSOR IMPACTS

MAZ 543 12 x 12 TRANSPORTER/launcher
for the SS-20 missile, adaptable for the SS-X-25.

~17 M.

~3 M

~3 M
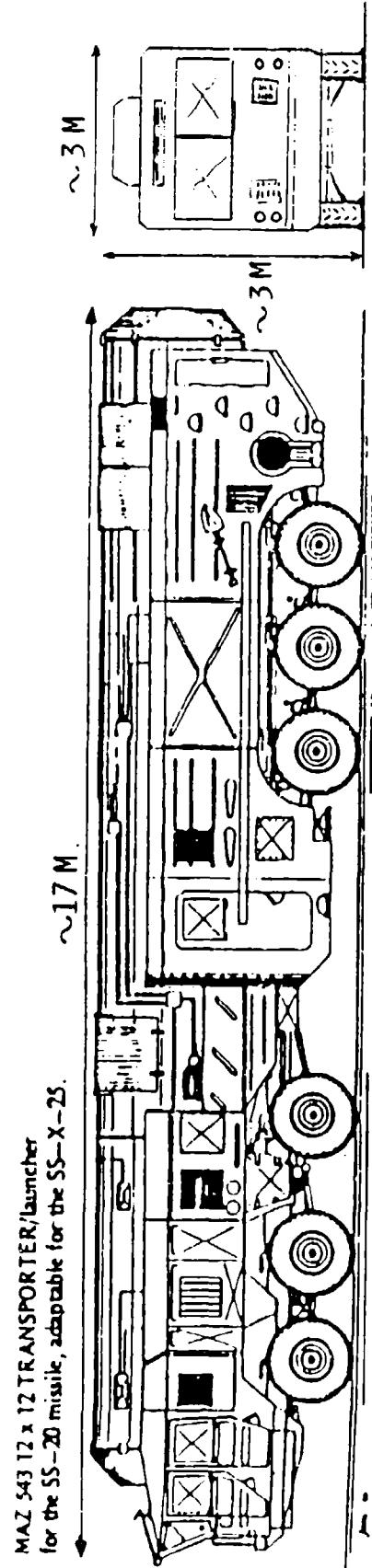
- TARGET DETECTION IN CLUTTERED BACKGROUND . ?UIRES PATTERN RECOGNITION ==>
  RESOLVE TARGET SCATTERING CENTERS

- ASSUMED MINIMUM REQUIREMENT:
  - 1 M RESOLUTION (1 FOOT NEEDED ?)
  - 10 dB SNR ON 1 M**2 DISCRETE

- NEED HIGH Pd, LOW Pfa. (ATR PERFORMANCE NOT CONSIDERED)

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BISTATIC SAR SYSTEM

Now we begin to describe the concept in more detail and summarize its performance against the assumed requirements.

A potentially serious operational problem for any bistatic radar system is coordinating the transmitter and receiver to have both their antennas pointing at the common area or object of interest. In order to solve this problem, this concept relies on the satellite transmitter illuminating the entire dispersal region surrounding the MOB (MOB region) thus providing coordination in space. In order to provide coordination in time as well, we require a constellation of satellites to provide continuous coverage of the MOB so that whenever the aircraft is over the MOB region, bistatic operation is possible.

Within the MOB region, the aircraft forms a bistatic SAR map in the so-called strip map mode. In this mode, the imaged area is typically located to either side of the aircraft. As the aircraft flies along, the mapped region is swept out as a swath. The coverage rate provided by this mapping system is simply the aircraft velocity times the total swath width (perpendicular to the ground velocity). This swath width is an important figure of merit for the imaging system. Unless otherwise stated, the aircraft is assumed to fly along at 10 km altitude at a speed of 200 meters per second.

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BISTATIC SAR SYSTEM

XMIT BEAM

EARTH SURFACE

MOB REGION 185 km RADIUS

10 km

RCV BEAM FOOTPRINT

SWATHS

SATELLITE HORIZON
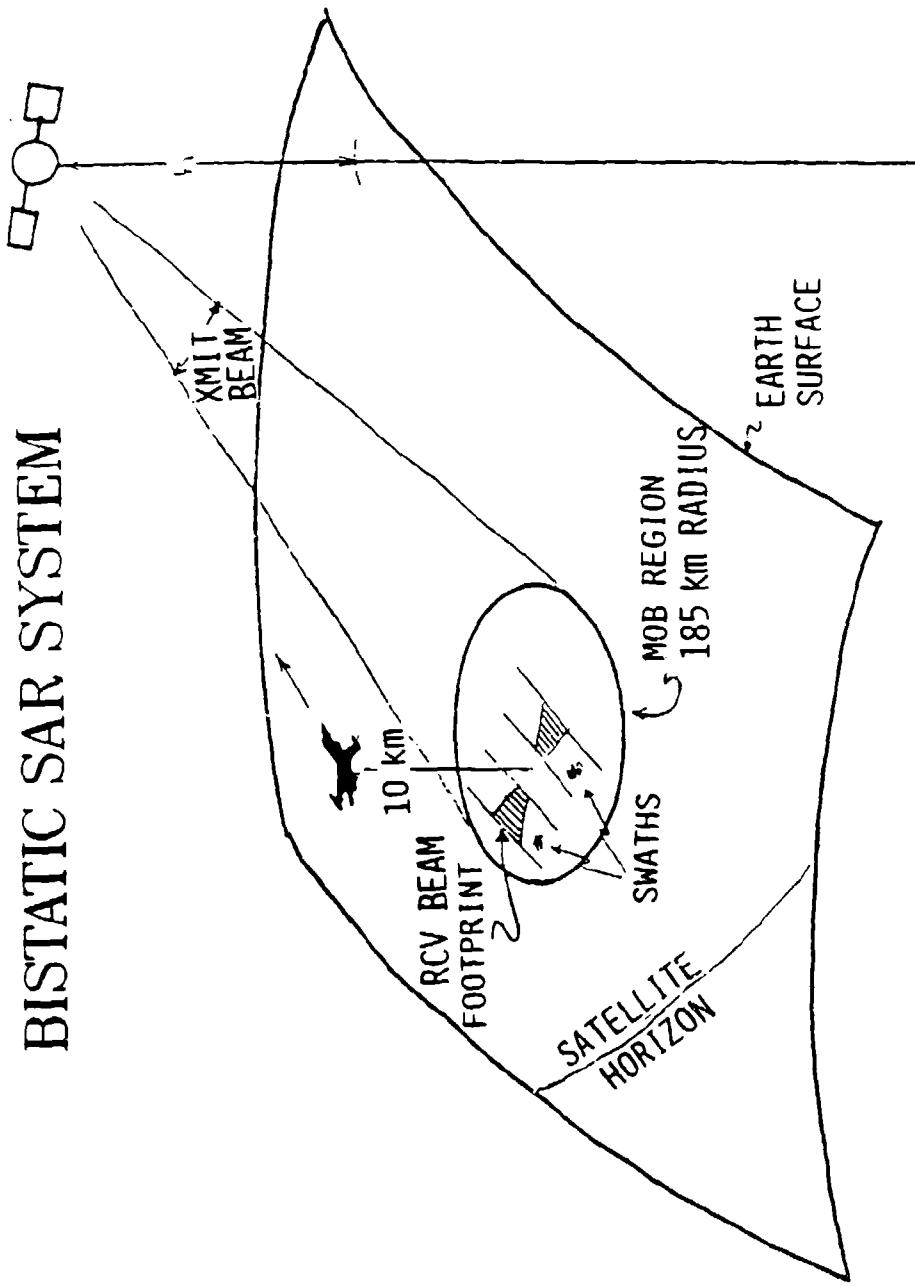
- SATELLITE ILLUMINATES ENTIRE MOB REGION TO SIMPLIFY COORDINATION
  - CONSTELLATION PROVIDES CONTINUOUS COVERAGE OF ALL MOB REGIONS

- BOMBER IMAGES IN STRIP MAP MODE
  - COVERAGE RATE = BOMBER VELOCITY (200M/S) X SWATH WIDTH (TBD)

TARGET VISIBILITY IMPOSES MINIMUM GRAZING ANGLE

This chart suggests a basic trade-off between maximizing radar coverage from a platform a some fixed altitude, and maximizing the probability of seeing the target within the area covered. If we assume that the SS-25s hide by simply parking on a roadside next to the trees, then given an azimuth angle from the target, a certain minimum grazing angle is required to see the target (see upper-left). Inversely, for a fixed grazing angle, randomly oriented road segment containing the target, and assumed road width and tree height, we can compute the probability of having a clear line of sight (C-L-O-S) to the target. The lower-left graph illustrates this calculation.

The strip map SAR views a continuum of grazing angles from a maximum of 90 degrees to some minimum (see upper right). Assuming targets to be uniformly distributed in the swath region, and road segments to be oriented uniformly with respect to the aircraft ground velocity, then we compute the probability of seeing all the targets within the swath by integrating the Pr[CLOS] over the range of grazing angles subtended by the swath. This calculation is shown in the lower right graph. Note that if the minimum grazing angle is high, the probability of seeing all targets within the swath is very good but the swath is very narrow. The alternate time scale shown in the lower right graph indicates how much time it takes for a single aircraft to search one half of an MOB dispersal region with a swath of corresponding minimum grazing angle. If the minimum grazing angle is 45 degrees, the probability of seeing the targets within the 20 km. swath (10 km altitude A/C) is 0.5 and it would take a single aircraft 4 hours to search one half the MOB dispersal region (assuming 100 nmi radius). This calculation only applies to the bistatic case when the satellite is overhead. This assumption is not a bad one in the strawman design as we will see.

TARGET VISIBILITY IMPOSES MINIMUM GRAZING ANGLE

- SS-25s UNIFORMLY DISTRIBUTED IN MOB DISPERSAL REGION
- ROAD SEGMENTS WITHIN SWATH RANDOMLY ORIENTED
- SATELLITE OVERHEAD

ASSUMED TREE HEIGHT = 10 M

ASSUMED ROAD WIDTH = 10 M

MIN. GRAZING ANGLE
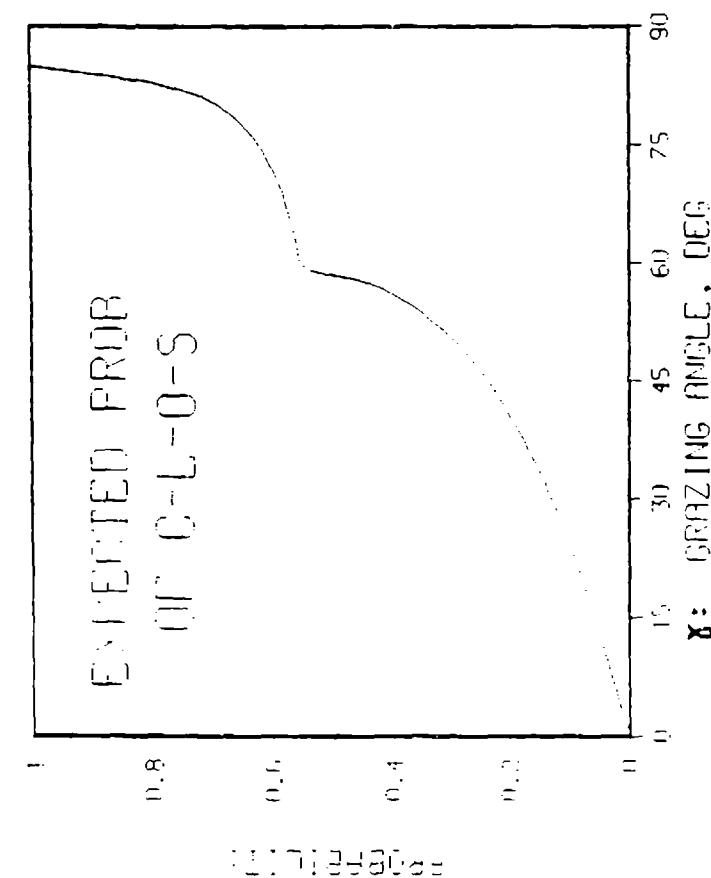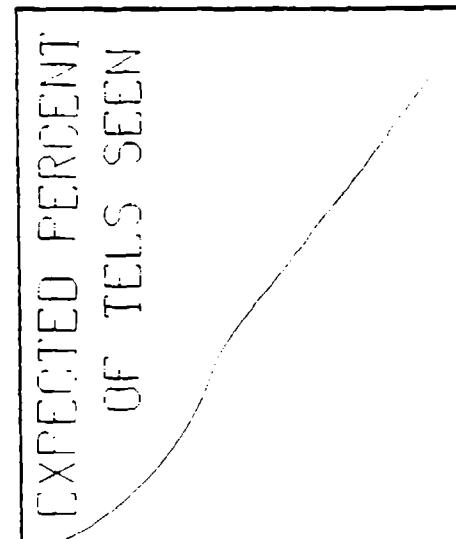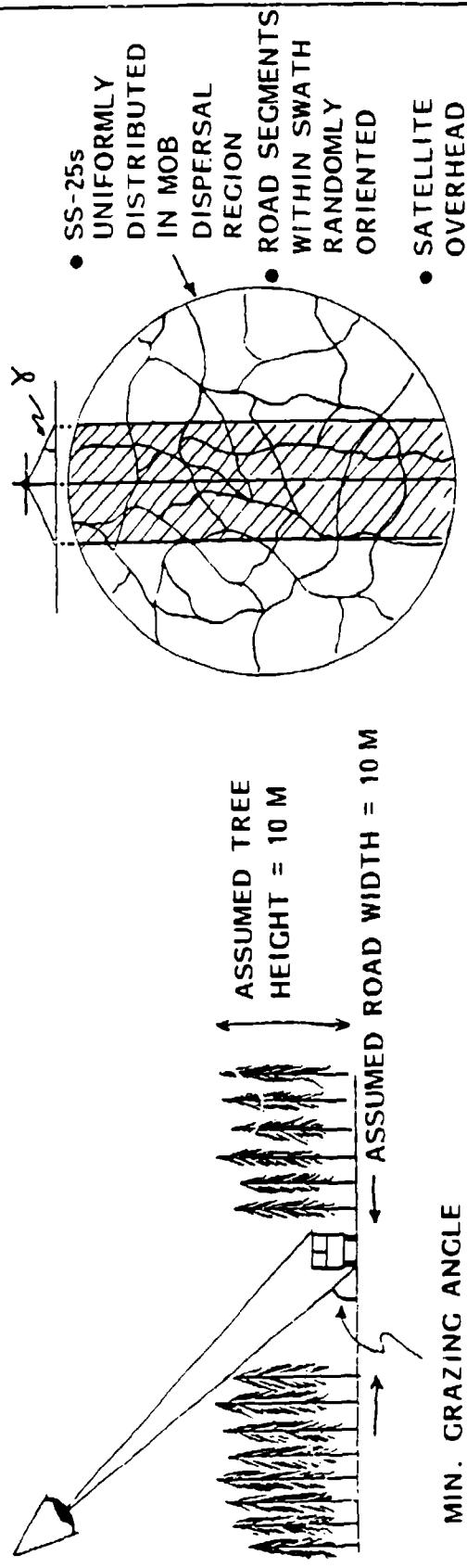
SCOPE OF SATELLITE COVERAGE ANALYSIS

The goal of the satellite coverage analysis was to determine the minimum number of satellites in a constellation to provide continuous coverage of the MOB regions. For circular orbits, this depends primarily on the satellite altitude but also on orbit inclination and the minimum grazing angle allowed on illumination. We also considered non-circular orbits. We have found that the elliptical Molniya orbit offers the minimum constellation size.

SCOPE OF SATELLITE COVERAGE ANALYSIS

- DETERMINE NO. SATELLITES TO PROVIDE CONTINUOUS COVERAGE

  - PRE-DEPLOYED, PERMANENT CONSTELLATION
 - SIOP DEPLOYMENT

    VS.

- SATELLITE ALTITUDE
  - LOW ALTITUDE (1000 KM) CIRCULAR ORBIT
  - HIGH ALTITUDE (GEOSYNC.) CIRCULAR ORBIT
  - MOLNIYA ORBIT

- ORBIT INCLINATION

- MINIMUM TRANSMIT GRAZING ANGLE

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REQUIRED NUMBER OF SATELLITES

This chart shows the number of satellites in circular orbit required to have continuous coverage of the MOB regions as a function of satellite altitude. The curves are parameterized by the minimum allowable grazing angle on illumination. The curves indicate the strong motivation for going to higher altitude to reduce the number of satellites required. The calculation used to plot these curves did not take advantage of possible time synchronization of the satellite's orbit and the Earth's rotation period.

REQUIRED NUMBER OF SATELITES

-- CIRCULAR ORBITS --

MINIMUM GRAZING ANGLE:

60

45

30

15

NUMBER OF SATELLITES

SATELLITE ALTITUDE, KM

45
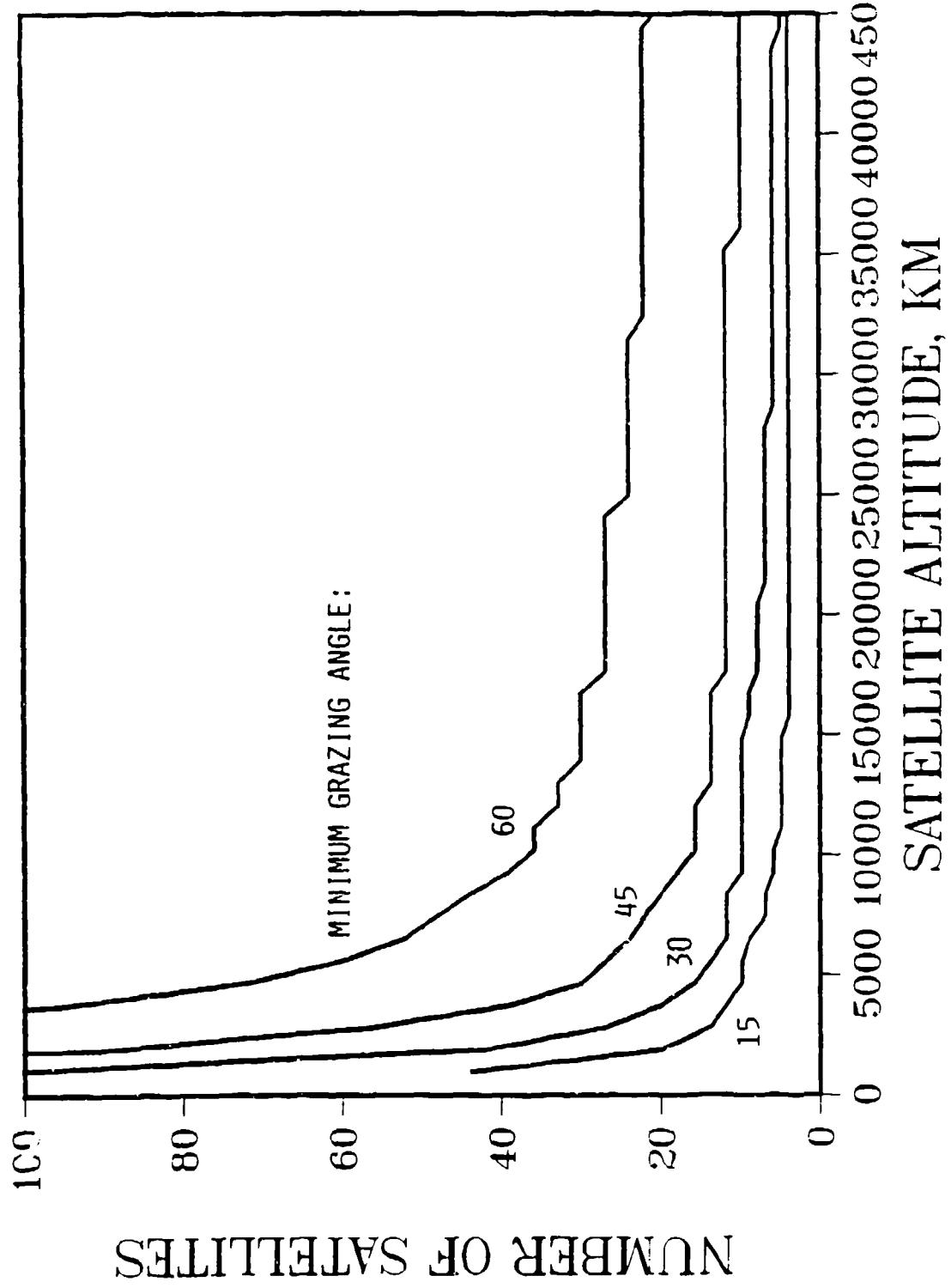
NOTIONAL MOB DISPERSAL REGIONS

This map shows the Earth in a North-pole projection with the MOB regions notionally added to the map. The next four charts are overlays on this map of the coverage provided by particular satellite constellations.

NOTIONAL MOB DISPERSAL REGIONS
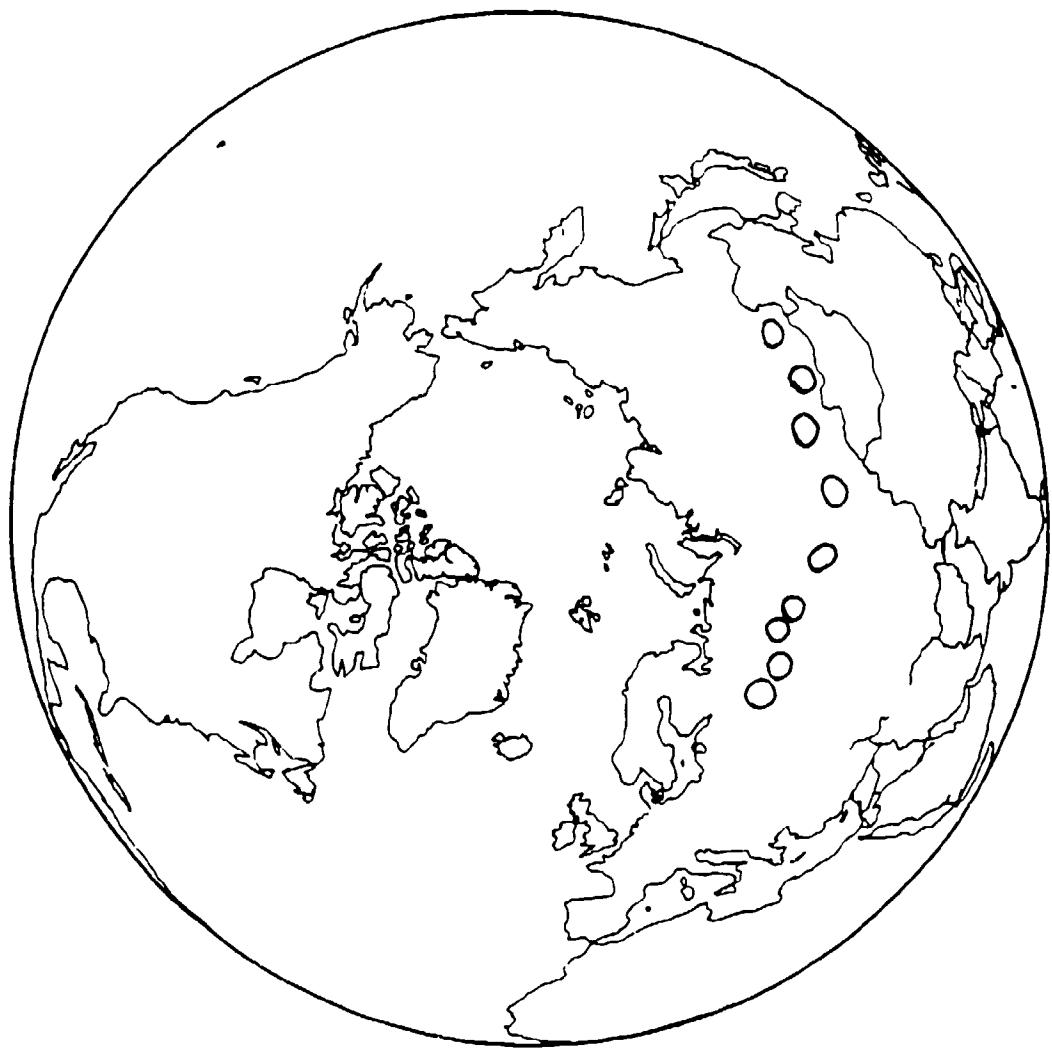
COVERAGE OF 1 GEOSTATIONARY SATELLITE

This overlay indicates that if a minimum illumination grazing angle of 15° were acceptable, then a single geostationary satellite could provide continuous coverage of all MOB regions. Since the minimum acceptable grazing angle for illumination is much higher, at least 45°, this same satellite cannot provide coverage.

COVERAGE OF 1 GEOSTATIONARY SATELLITE

15°

30°

45°

MINIMUM GRAZING
ANGLE

49
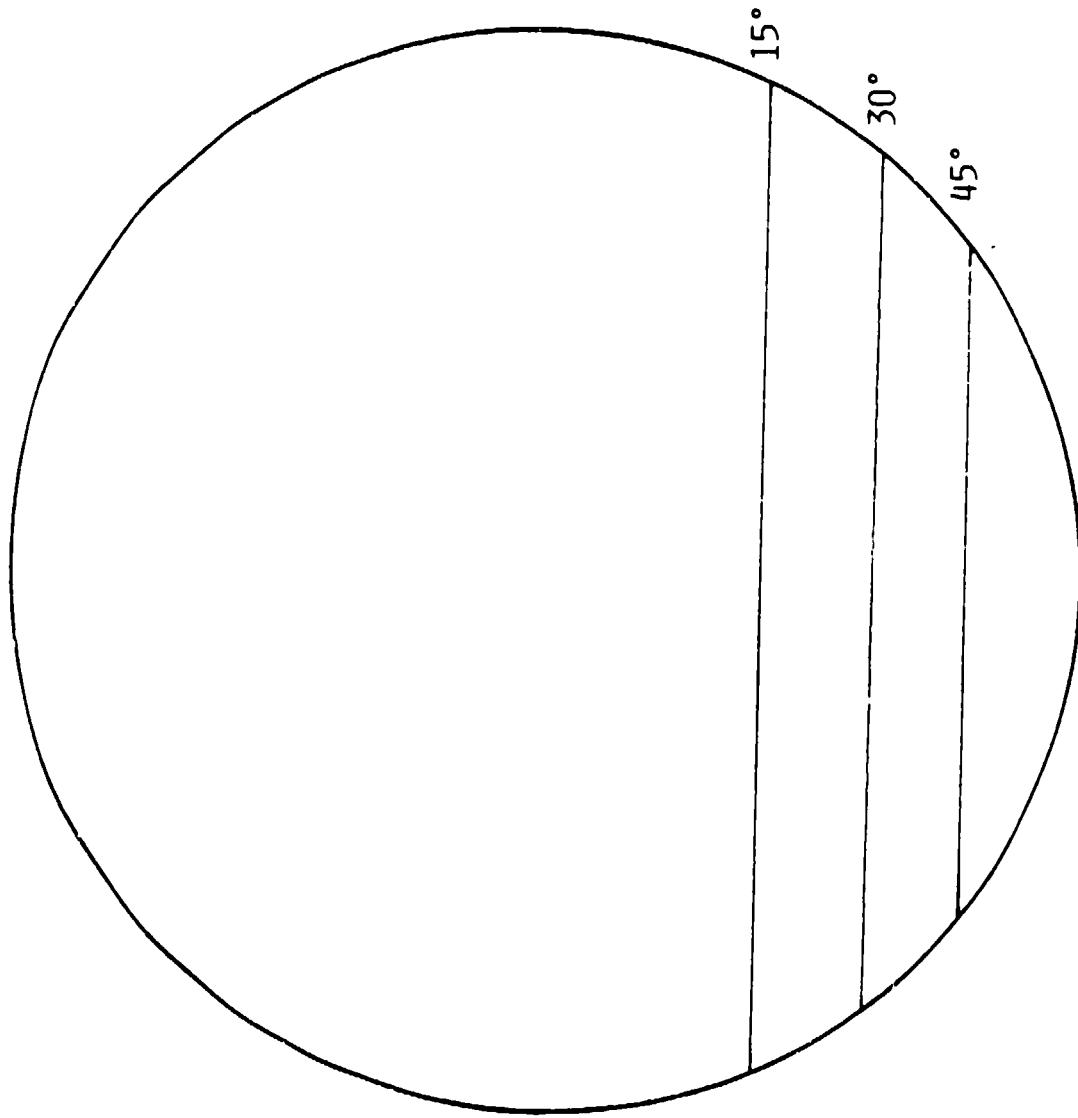
COVERAGE OF 4 GEOSYNCHRONOUS SATELLITES

50° INCLINATION, 45° MINIMUM GRAZING ANGLE

If the orbit plane of a geosynchronous altitude satellite is inclined to 50°, then a constellation of four satellites provides continuous coverage. Each satellite provides coverage for six hours. The overlay shows that coverage footprint at the beginning, halfway point, and end of the on-station period, the intersection of which shows the required coverage with a minimum grazing angle of 45°.

COVERAGE OF 4 GEOSYNCHRONOUS SATELLITES
## 50° INCLINATION, 45° MIN. GRAZING ANGLE
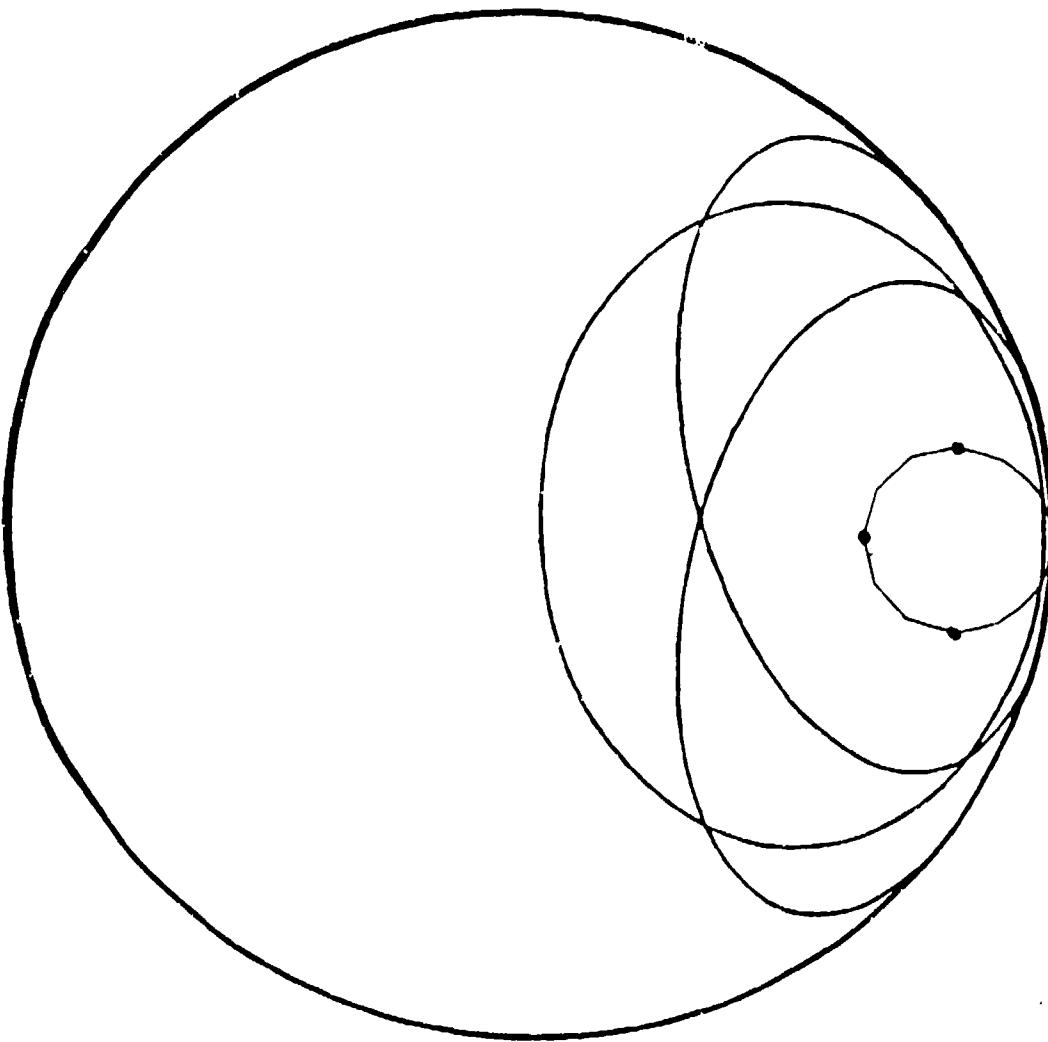
COVERAGE OF 3 MOLNIYA SATELLITES

50° INCLINATION, 45° MINIMUM GRAZING ANGLE

This overlay shows that a constellation of three, 12-hour period, inclined, elliptical, Molniya orbits provides continuous coverage with a minimum grazing angle of 45°. The 45° footprints indicate more than adequate coverage. In fact, the minimum grazing angle to the MOB regions is 58°. This constellation has the fewest number of satellites of any we found given a requirement of 45° minimum illumination grazing angle.

Each of the three satellites is on-station for eight hours, which raises the possibility of using a single such satellite to provide continuous coverage during the bombers' mission time over the Soviet Union if the satellite could be launched or maneuvered into the proper orbit at the right time. We call this option SIOP deployment.

During the on-station time, the satellite is at a very high altitude; at or slightly above geosynchronous altitude. As we show next, the required power and aperture, even at these altitudes, seem reasonable.

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COVERAGE OF 3 MOLNIYA SATELLITES
45° MIN. GRAZING ANGLE

• SINGLE SAT. PROVIDES COVERAGE FOR EIGHT HOURS

53
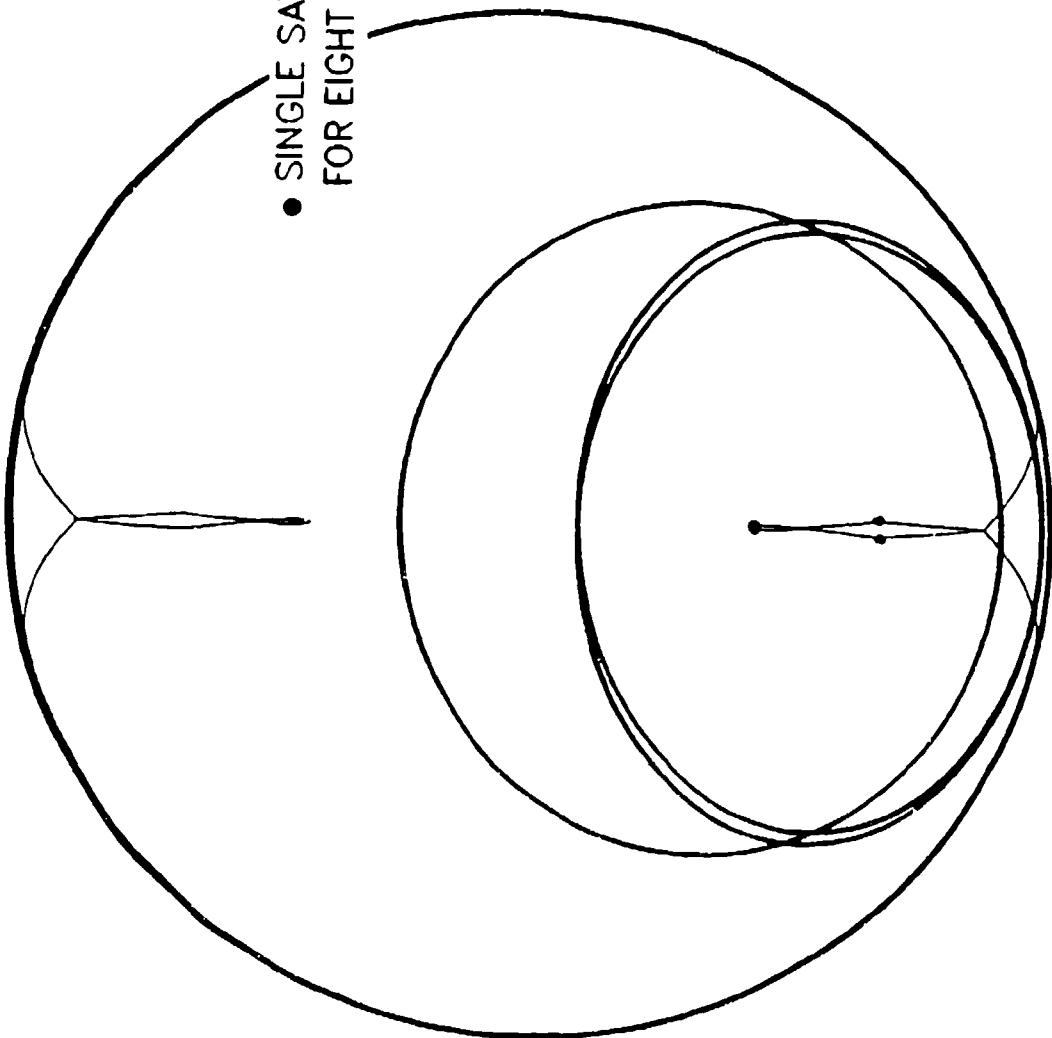
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COVERAGE OF 3 MOLNIYA SATELLITES
60° MIN. GRAZING ANGLE
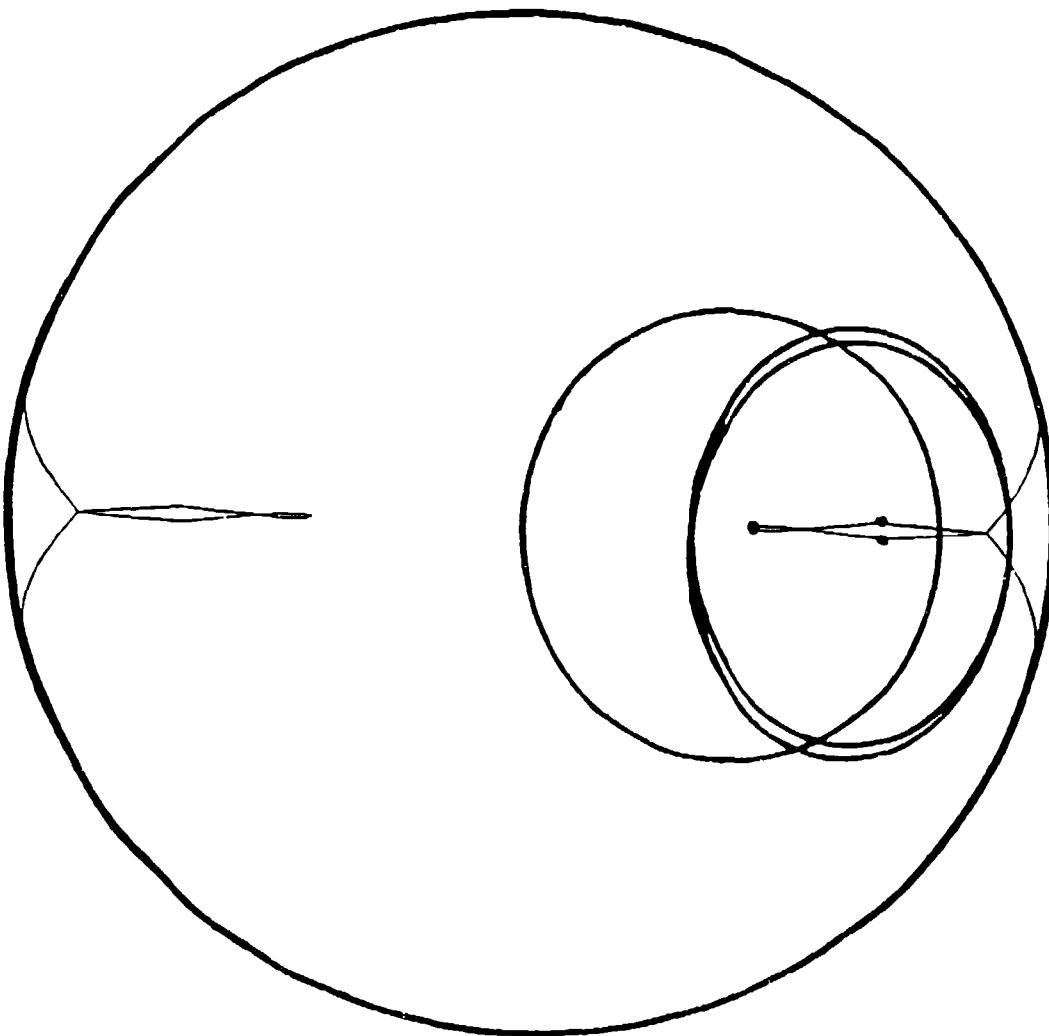
BISTATIC SAR SYSTEM

We now describe the bistatic radar operation in a little more detail. With the satellite illuminating the entire MOB region, the bomber flies in the region and passively receives the energy reflected off the ground and processes this data to form a strip map. The receiver is assumed to use a phased array antenna to allow maximum flexibility in shaping the antenna footprint to maximize coverage and maintain adequate resolution (1 meter in range and cross-range) as well as adequate signal-to-noise ratio (10 dB).

Since the high altitude satellites must provide coverage over multiple MOBs while on-station, they use an agile beam system (phased array, or phased array feed with a reflector) to time multiplex on a pulse-by-pulse basis illumination of all MOB regions.

BISTATIC SAR SYSTEM
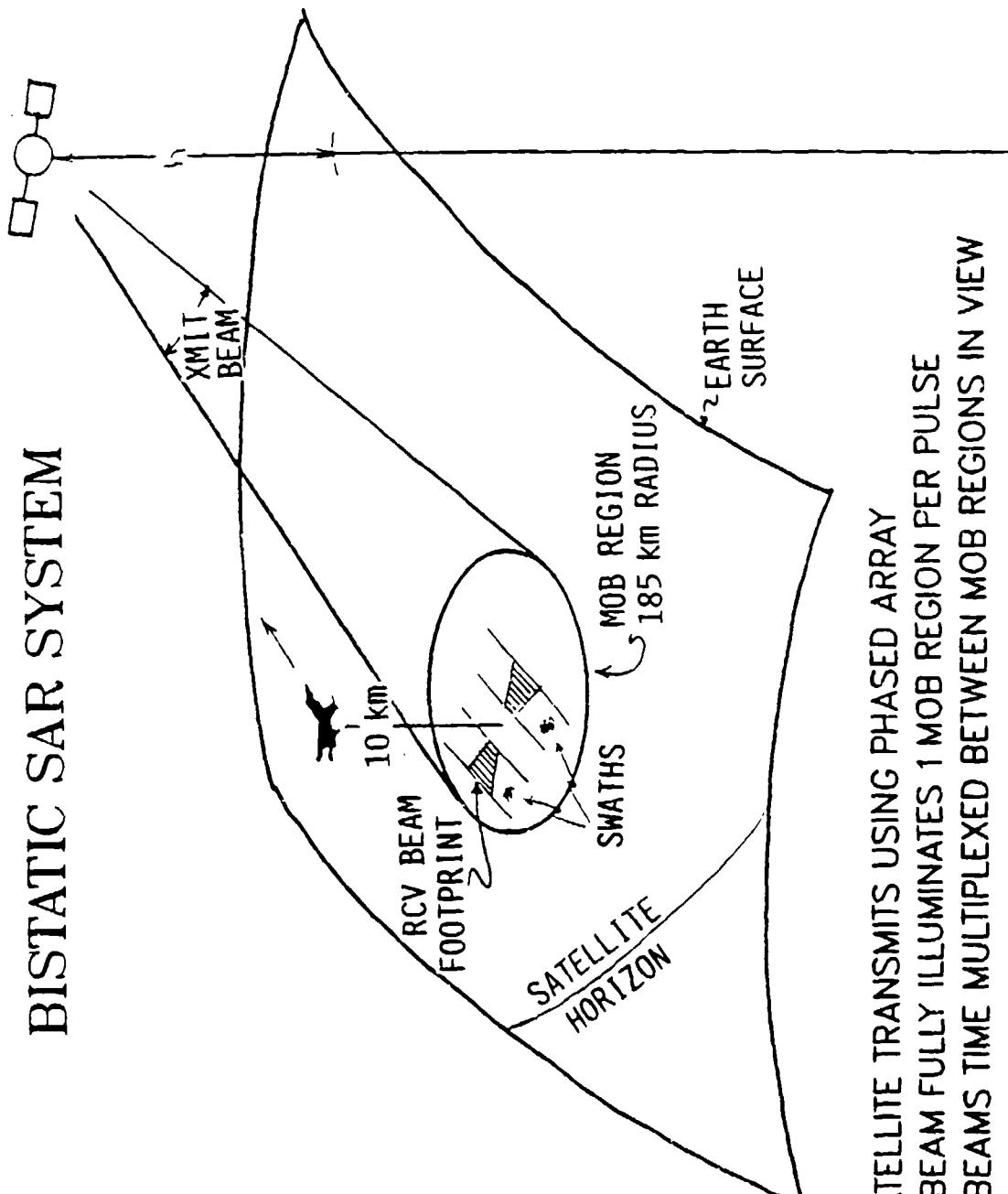
- SATELLITE TRANSMITS USING PHASED ARRAY
  - BEAM FULLY ILLUMINATES 1 MOB REGION PER PULSE
  - BEAMS TIME MULTIPLEXED BETWEEN MOB REGIONS IN VIEW

- AIRCRAFT RECEIVES USING PHASED ARRAY & PROCESSES
  - STRIP MAP MODE EMPLOYED
  - COMPLEX BEAM FOOTPRINT

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SCOPE OF RADAR ANALYSIS

This chart lists the radar parameters considered in the requirements analysis. The requirements were developed as a function of satellite altitude and minimum transmit grazing angle.

Throughout this analysis we assume the radar operates at a 10 GHz frequency with a maximum instantaneous bandwidth of 500 MHz and a maximum coherent dwell time of 10 seconds. These particular choices are not absolute requirements but seem like reasonable parameters and give balanced performance.

SCOPE OF RADAR ANALYSIS

DETERMINE:

- TRANSMIT POWER REQUIREMENTS
- RADAR BANDWIDTH AND INTEGRATION TIME
- RANGE AND CROSS-RANGE RESOLUTION
- PRF
- ACHIEVABLE SWATH WIDTH
- RECEIVE ANTENNA GAIN

VS.

- SATELLITE ALTITUDE
  - LOW ALTITUDE (1000 KM) CIRCULAR ORBIT
  - HIGH ALTITUDE (GEOSYNC.) CIRCULAR ORBIT
  - MOLNIYA ORBIT
- MINIMUM GRAZING ANGLE LIMITS
  - 45 DEG.
  - 30 DEG.
  - 15 DEG.

EXAMPLE: *LOW ALTITUDE SATELLITE COVERAGE*

This illustration reiterates the point that the low altitude satellite may not have to provide coverage for all MOB regions simultaneously and so the average power requirements for this case are lower than for the high altitude case. However, the required number of satellites is greater.

60

EXAMPLE: LOW ALTITUDE SATELLITE COVERAGE
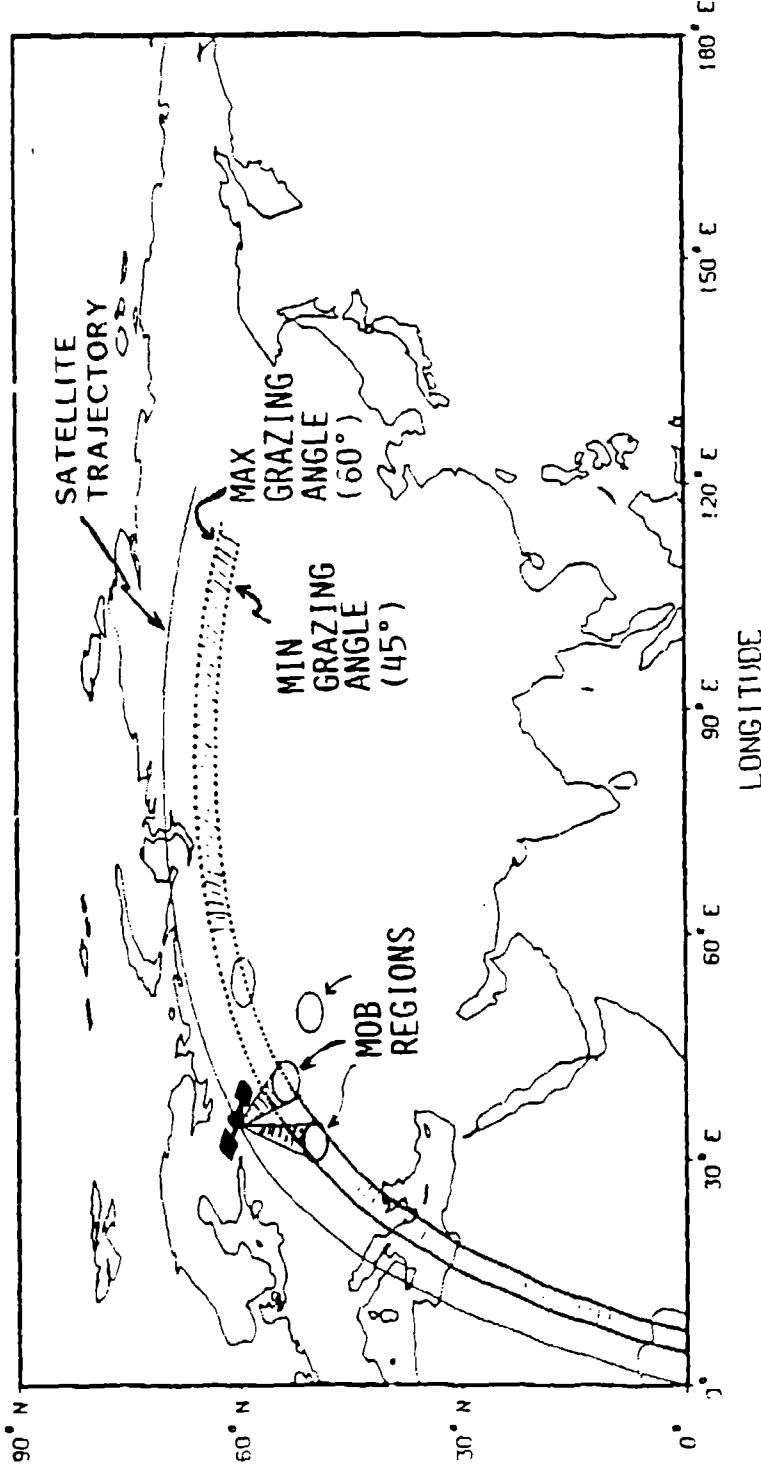
- LOW ALTITUDE ORBIT
  - ONLY A FEW MOBS IN VIEW SIMULTANEOUSLY

- HIGH ALTITUDE ORBIT (OR MOLNIYA)
  - ALL MOBS IN VIEW, BUT
 - ONLY THOSE WITH BOMBERS NEED BE RADIATED

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POWER IS INDEPENDENT OF SATELLITE ALTITUDE

If the satellite is not required to illuminate outside the MOB dispersal region, the system efficiency can be maximized by sizing the transmit antenna to just cov... the MOB region. At geosynchronous altitudes this results in the satellite's antenna being 6.5 m x 4.5 m. At lower altitudes, the required antenna is smaller. A result of this assumption is that the power is now independent of satellite altitude since the energy density on the ground is held constant by assumption (see inset diagram).

The curves show the required transmit power to maintain 10 dB SNR on a 1 m**2 discrete representative of a target scattering center. The power is a function of receive grazing angle (related to receive range) as well as the assumed receive aperture size on the aircraft. The scale gives the required power on a per-MOB basis, thus applicable to satellites of any altitude. For high altitude satellites such as the Molniya constellation, the number of MOBs simultaneously in view is roughly 10, thus the indicated power must be multiplied by 10 to get the total radiated power required of each Molniya satellite.

The required power for a minimum receive grazing angle of 45 degrees (20 km max. swath) is 350 W to 1.4 kW. If a wider swath is desirable (lower minimum grazing angle and lower probability of CLOS), then the required power increases. But even for a 75 km swath (15 degree min. grazing angle), if a 1 m**2 receive aperture is acceptable, then the power required (2.6 kW) is not heroic.

POWER IS INDEPENDENT OF SATELLITE ALTITUDE

63
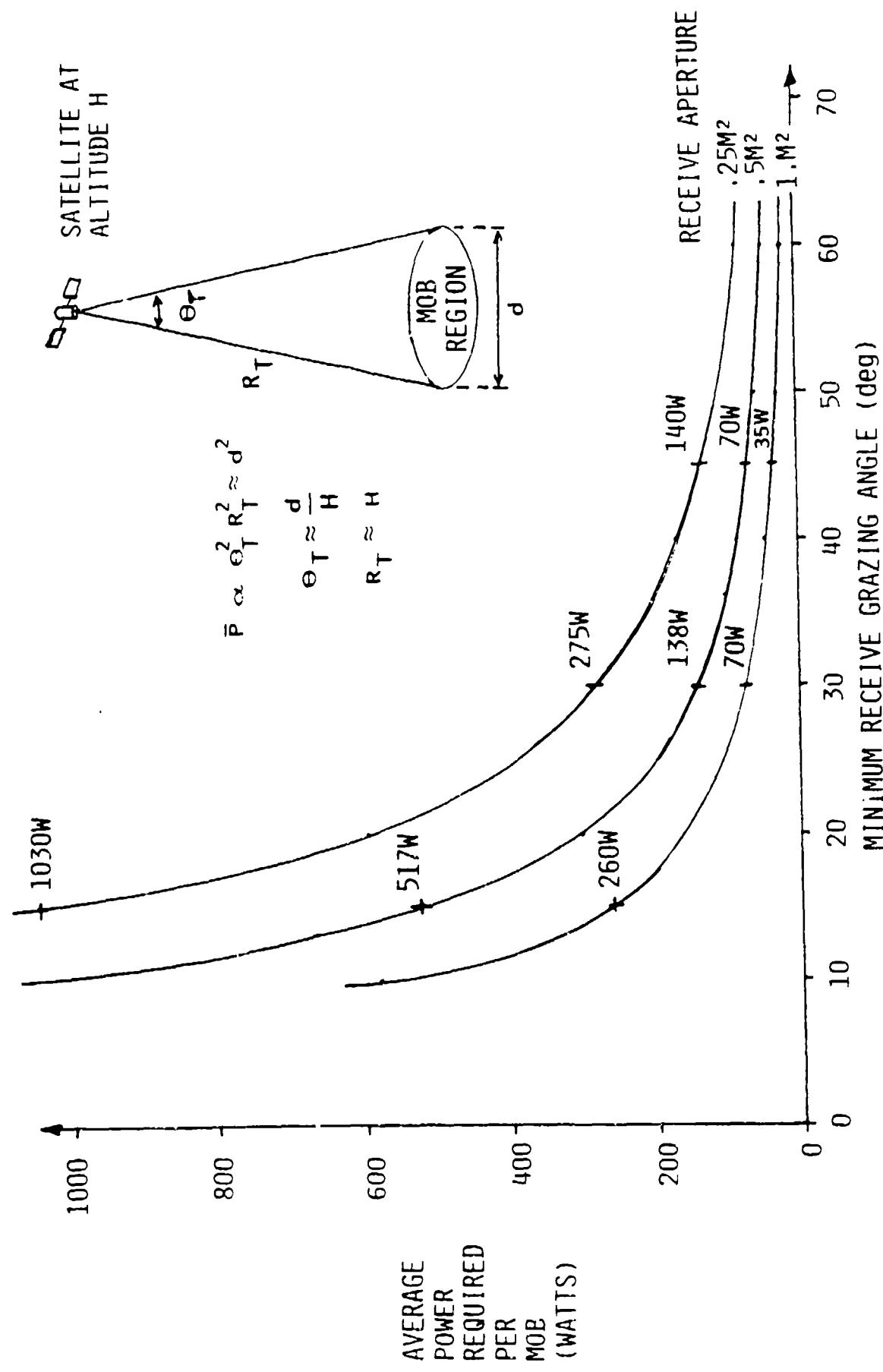
RESOLUTION LIMITS ON COVERAGE

We now turn to the issue of coverage performance as limited by resolution. Toyon has developed a computer program which plots regions on the ground which satisfy desired resolution constraints given the details of the particular bistatic geometry. This plot shows the aircraft in the middle flying "south" and indicates the regions which satisfy the 1 m resolution in range and cross-range requirement. The areas which look like two cookies with bites in them are regions where the resolution is better than 1 m, elsewhere the resolution is worse than 1 m.

The plot is specific to the aircraft geometry as indicated and the satellite located at 45 degrees clockwise from "north" at a range and altitude corresponding to a 45 degree transmit grazing angle from a Molniya satellite at apogee. One lesson we learned from studying plots of this type is that the orientation of the velocity vector of the high altitude satellite has very little effect on the resolution plot.

The next three charts are overlays to this plot and indicate why the "good" region looks as it does in this particular geometry. The details of the resolution program and results from other geometries can be found in the appendix.

RESOLUTION LIMITS ON COVERAGE

EXAMPLE: MOLNIYA ORBIT, 45° TRANSMIT GRAZING ANGLE

SATELLITE
LOCATION

BANDWIDTH = 500 MHz
ARRAY TIME = 10 S,

RESOLUTION
REQUIRED =
1 M OR BETTER

"GOOD" REGION

AIRCRAFT

"GOOD" REGION
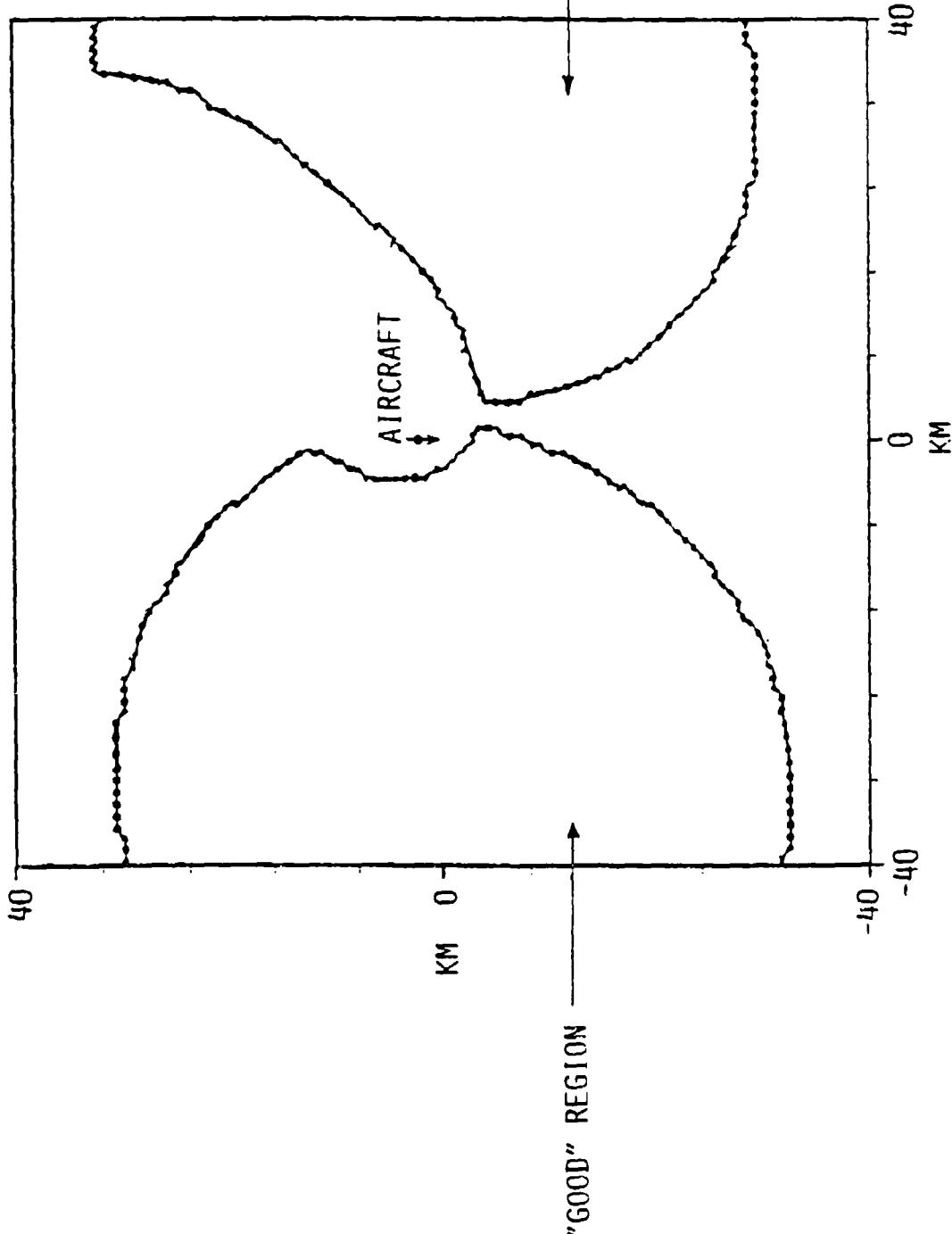
BISTATIC RANGE RESOLUTION

This overlay to the preceding chart shows contours of constant bistatic range-sum (range for short) resolution for the specific geometry. The oval region in the upper right is the area where bistatic range resolution is degraded to something worse than 1 m. This region is the bistatic analog to the "Nadir hole" in the monostatic case.

BISTATIC RANGE RESOLUTION
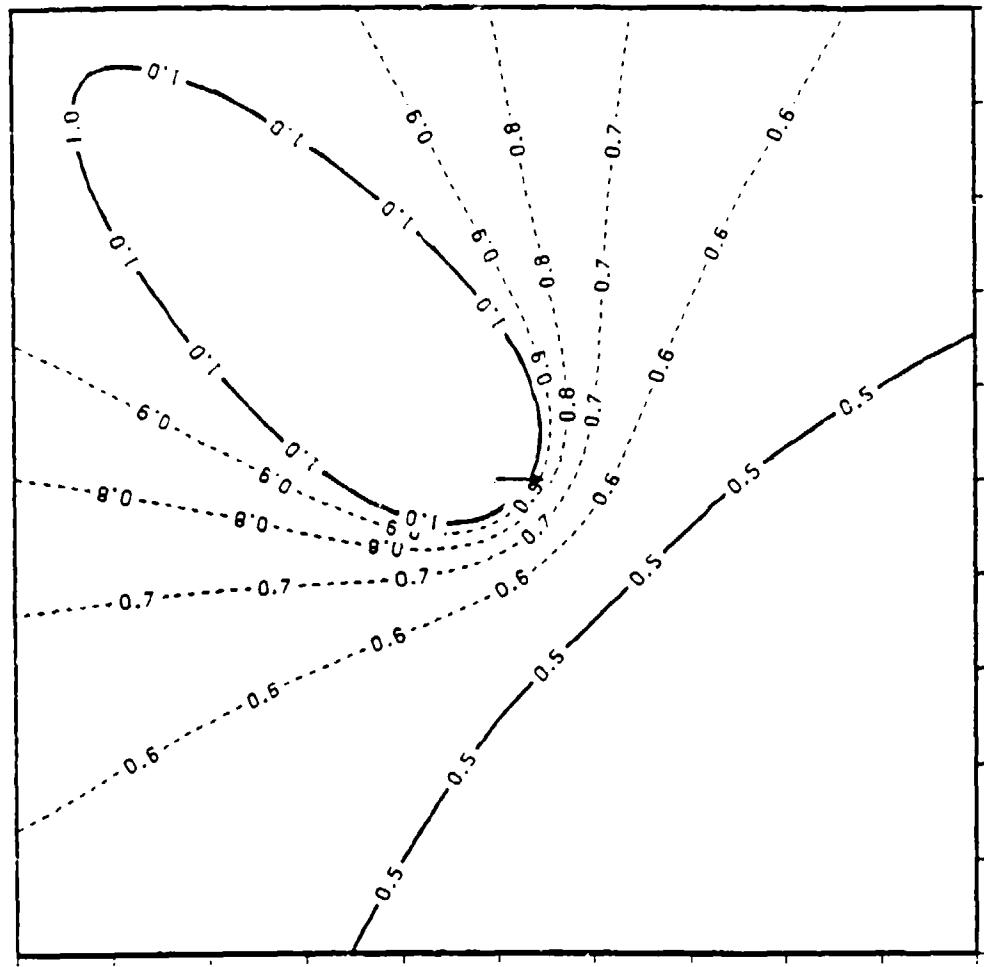
BISTATIC CROSS-RANGE RESOLUTION

This overlay shows contours of constant cross-range resolution as generated by using doppler resolution projected into the direction orthogonal to the range resolution vector (see appendix for details). The cross-range resolution contour of 1 m provides the outline for the "good" regions shown in the first resolution chart, while the range resolution contour of 1 m produces the "bites" in the otherwise symmetrical outline.

BISTATIC CROSS-RANGE RESOLUTION
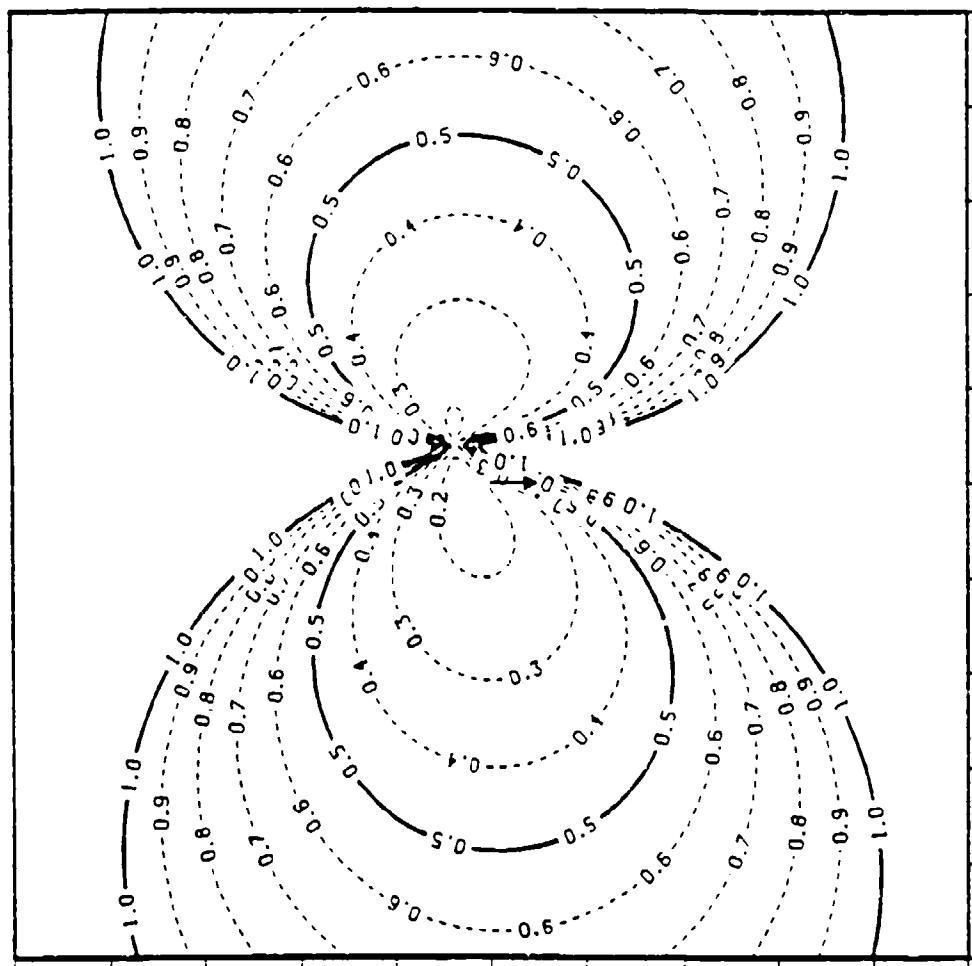
BISTATIC DOPPLER RESOLUTION

This overlay shows contours of constant doppler resolution. Doppler is the mechanism for separating targets at the same range but different azimuth bearing. Since we are interested in how targets can be resolved in the cross-range dimension, we examine how well doppler resolution can be used to provide cross-range information next.

BISTATIC DOPPLER RESOLUTION
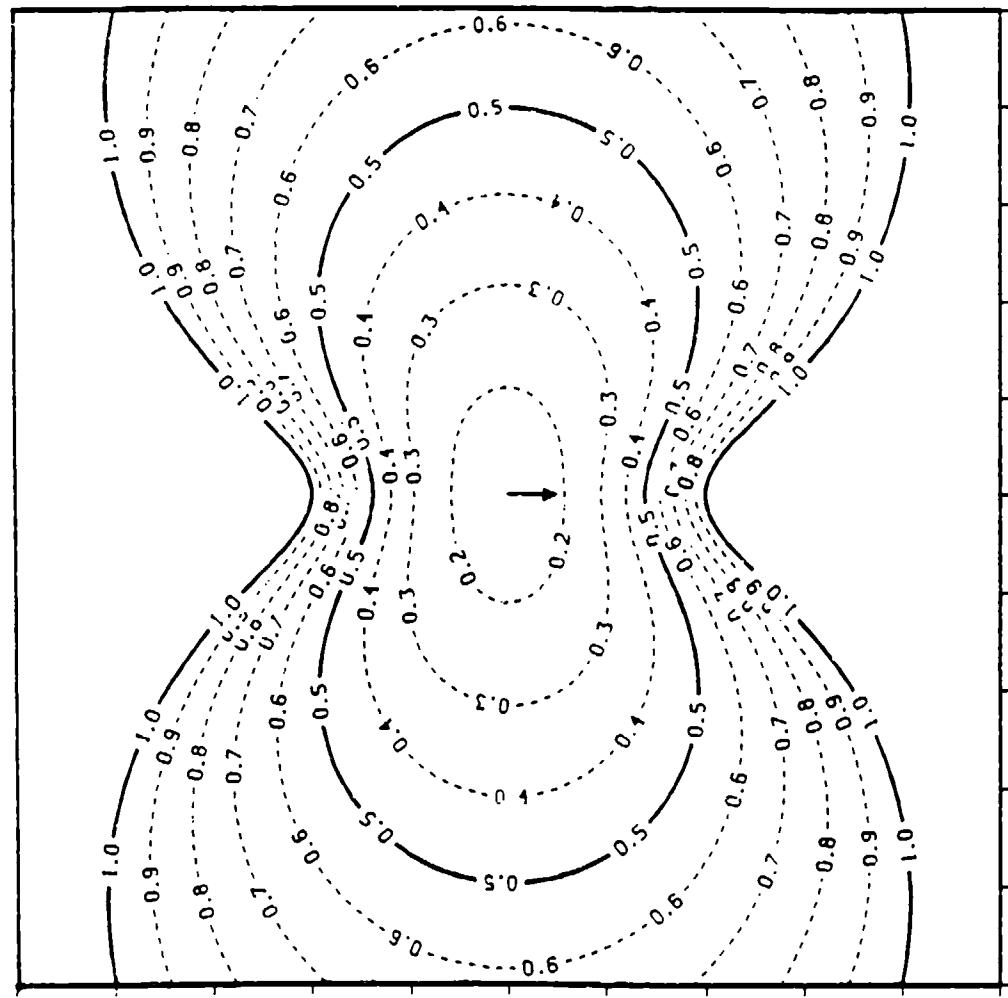
ACHIEVABLE SIDE-LOOKING SWATH

This overlay to the first resolution chart shows how far the two-sided strip map swath can extend using only side-looking antennas on the aircraft. The swath must fall within the "good" resolution regions on the ground and be within the minimum grazing angle horizon limits (indicated by the circles. The table shows that for this geometry, the swath width can be 60 km. for a 15 degree minimum grazing angle down to only 7 km. for a 45 degree min. grazing angle.

Note again that the results are only valid for the particular geometry shown in this example. To understand overall system performance requires examination of all possible illuminator/receiver geometries which we will summarize next.

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ACHIEVABLE SIDE-LOOKING SWATH
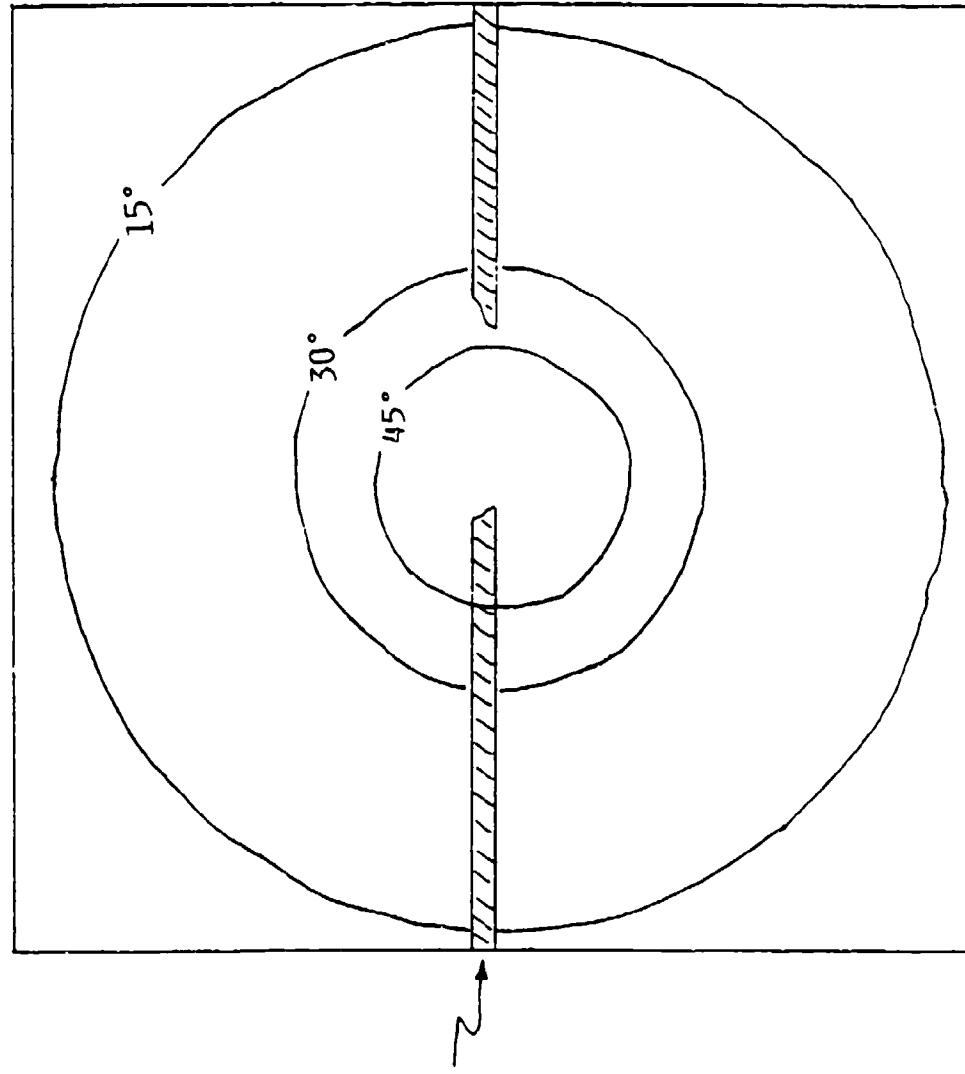
| MIN. GRAZING ANGLE	TOTAL SWATH WIDTH
45°	7 Km
30°	18 Km
15°	60 Km

ACHIEVABLE SIDE-LOOKING SWATH LIMITS

This graph summarizes the limits of swath width coverage due to sensitivity (SNR) limits, unambiguous range PRF limits, achievable resolution limits using a 500 MHz instantaneous bandwidth waveform, 10 second integration time, and averaging over satellite/aircraft geometries, and finally target visibility limits expressed as grazing angle for a 10 km altitude aircraft. Each of these limits is shown separately and the combined swath is the bottom curve.

From the graph we see that over the range of grazing angles which represent reasonable target visibility (> 15 degrees), the coverage is limited primarily by *minimum grazing angle* and not by any radar related constraints. Only at grazing angles less than 15 degrees does the achievable resolution become the limiting factor. This observation deemphasizes the somewhat arbitrary bandwidth and integration time assumptions since they only affect achievable resolution.

The coverage capability appears too limited to be useful for wide-area search for SRTs but adequate for occupancy check or limited cued-area search. A monostatic SAR suffers the same grazing angle limitation. It may be possible to extend the swath width coverage by flying the aircraft at higher altitude.

ACHIEVABLE SIDE-LOOKING SWATH LIMITS

HIGH ALTITUDE SATELLITE

SENSITIVITY LIMITED ($\bar{P}$ = 10 kW, A_r = 1 M²)

PRF LIMITED

RESOLUTION LIMITED (AVERAGE OVER SAT/A.C. GEOMETRIES)

GRAZING ANGLE LIMITED (10 km A/C ALT.)

COMBINED AVG SWATH

SWATH WIDTH (km)

MINIMUM GRAZING ANGLE (deg)
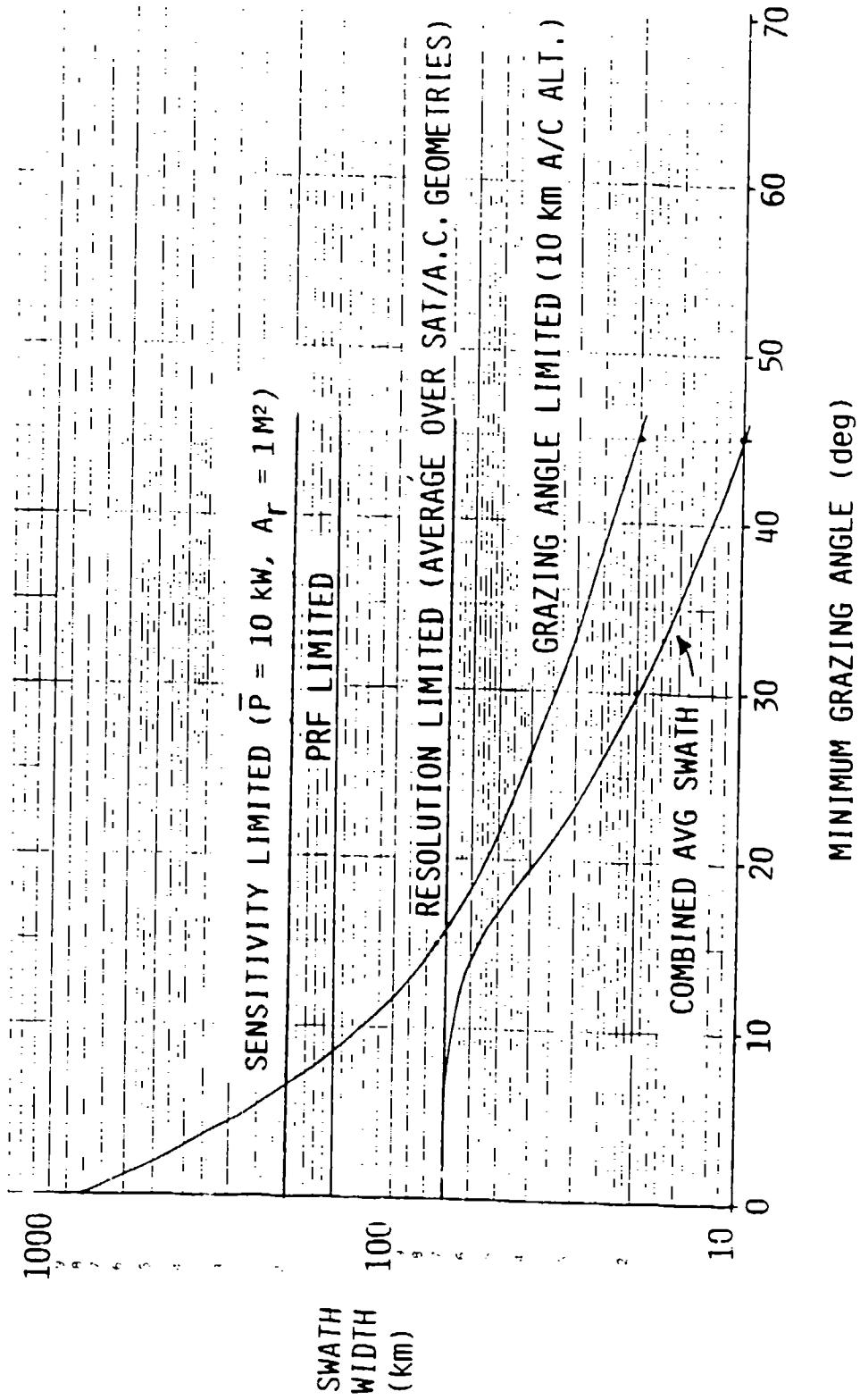
SYS 4 TRADES SUMMARY

Having summarized the analysis performed over the course of the pilot study, we recap the configurations considered and select a strawman design. The favored design utilizes 3 Molniya satellites to provide continuous coverage over all the MOB regions with a 58 degree minimum grazing angle on transmit. Each satellite uses a 4.6 m x 6.5 m antenna and radiates 1.4 kW average power. Each bomber is assumed to carry a single downward looking .5 m x .5 m receive antenna which forms multiple stacked beams in elevation scanned out to a 45 degree minimum grazing angle which results in an average useful swath width of 10 km. This may be compared with a monostatic aircraft which has a useful swath of 14 km under the same assumptions but must radiate.

SYSTEM TRADES SUMMARY

- REQUIRES 45° MINIMUM GRAZING ANGLE

	NO. SATS*	AVERAGE POWER**	SAT APERTURE	TOTAL SWATH WIDTH	CAVEATS
CIRCULAR ORBIT LOW ALT. (1000 Km)	100+	~.14 KW/MOB	.12m x .16m	TBD	
HIGH ALT. (GEOSYNC)	4	1.4 KW TOTAL	4.6m x 6.5m	10 km AVG.	GRAZING ANGLE TO 15°
GEOSTATIONARY	1	→	→	44.5 km	GRAZING ANGLE >45°
MOLNIYA	-+			10 km AVG.	
MONOSTATIC A/C	N/A	N/A	N/A	14 km	FORCE SIZE TBD

*ASSUMES CONTINUOUS COVERAGE OVER SOVIET UNION

**ASSUMES .5m x .5m RECEIVE APERTURE

+AS FEW AS 1 IF SIOP-DEPLOYED

OBSERVATIONS

This chart summarizes the important observations which have been made earlier in the text and on the charts.

While the concept does not solve the SRT problem (and in fact we have not addressed some of the really tough issues), the performance of such a bistatic ground imaging radar may be much better in a role where target visibility is not the limiting factor as it is in this role. It may be desireable to identify and explore those ground imaging missions where the passive nature of the receiver is paramount since this is the basic advantage of this bistatic system. In addition it may be possible to extend the concept beyond ground imaging to encompass more radar functions such as moving target detection.

OBSERVATIONS

- FUNDAMENTAL TECHNOLOGIES HAVE BEEN SUCCESSFULLY DEMONSTRATED

- FEW SATELLITES REQUIRED (3) FOR CONTINUOUS COVERAGE WITH A MINIMUM GRAZING ANGLE OF >45 DEGREES.
  - CONT. MOB ILLUMINATION SOLVES COORDINATION PROBLEM

- TRANSMIT POWER INDEPENDENT OF SATELLITE ALTITUDE, POWER AND APERTURES ARE NOT HEROIC

- BISTATIC SAR SWATH WIDTH LIMITED BY OBSCURATION, NOT RADAR
  - MONOSTATIC A/C SUFFERS SAME
  - OK FOR OCCUPANCY CHECK, SMALL AREA CUE

- ISSUES REMAIN (NOT UNIQUE TO BISTATIC):
  - IDENTIFYING TELS IN IMAGERY WITHOUT EXCESSIVE FALSE ALARMS
  - EXPECTED FRACTION OF TELS SEEN VS. SRT MISSION TIME
  - CAMOUFLAGE, CONCEALMENT, DECEPTION

- OTHER GROUND IMAGING MISSIONS COULD BENEFIT FROM ARCHITECTURE
  - INTEL GATHERING (SR-71 FOLLOW-ON ?)
  - OTHERS: TACTICAL BATTLEFIELD SURVEILLANCE, NAV. RADAR, BOMB DAMAGE ASSESSMENT

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CHAPTER 3
TACTICAL APPLICATIONS

H.I. Jacobson

INTRODUCTION

The following topics will be discussed:

- Requirements imposed upon the space-based illuminator
- Illuminator constellation designs that meet the requirements
- Requirements imposed upon the airborne SAR receiver
- Receiver designs that meet the requirements

In all cases that we discuss, the illuminator is in a satellite, and the SAR receiver is in an airborne platform — either a bomber, a fighter, or an unmanned air vehicle (UAV). The context is support of tactical air or ground operations.

The baseline mode of operation is that the satellite illuminates an area on the ground determined by its beamwidth. This is the spot size. Illumination is supported for a dwell time. During the dwell, the satellite may be moving or stationary but the beam is stabilized with respect to the ground. A stationary satellite can support infinite dwell times, but moving satellites cannot. After the required dwell the beam may be moved to illuminate another area. The revisit frequency is the number of dwells that the satellite can perform on the same area in a 24 hour period.

ILLUMINATOR REQUIREMENTS

Application requirements may be imposed upon the following illuminator characteristics:

- Spot size
- Dwell time
- Minimum grazing angle
- Revisit frequency
- Field-of-regard

We discuss each in turn.

ILLUMINATOR SPOT SIZE

For a fixed illuminator output power, the illuminator energy incident on a unit area of the earth surface is inversely proportional to the square of the spot diameter. Thus, small spots permit more sensitive SAR receivers or lower transmitter powers. However, the smaller the spot, the greater the degree of coordination required between the beam steering and the airborne receiver user. At one limit, the beam would have to follow a specific airborne receiver on its flight path and be there at the times when the receiver was imaging.

Another problem with small spots is that they do not allow multiple simultaneous users. A satellite system can be expensive and needs to have multiple users to justify its cost. Because of these considerations, we have selected a spot 200 miles in diameter. It provides adequate energy density to operate airborne SAR receivers, requires reasonable antenna size and transmitter power, and covers a military area on the ground that encompasses a Corp or Army-sized unit. Thus during a single placement of the beam, the satellite illuminator could support all users within an Army deployment area.

DWELL TIME PER REVISIT

Unless an illuminator is in geostationary orbit, it can dwell on a point on the ground for a limited time at each orbital pass. A given area on the ground must be illuminated for the time required for aircraft platforms, carrying the SAR receiver, to perform their ground mapping mission. The illuminator beam covers at one time a small theatre of operation, such as Kuwait in the Iraq war. This theatre encompasses the activities of several divisions and the illuminator dwell time must be long enough to support all airborne SAR platforms in operation in the theatre.

Airborne SAR platform operations are assumed coordinated with the illuminator revisit times. Nevertheless, the illuminator dwell times must be large enough to tolerate some error in scheduled time-on-target by aircraft. An off-hand estimate of plus/minus five minutes is offered for the ability to achieve time-on-target. Thus, the illuminator dwell time

must equal the sum of airborne SAR receiver mission time, plus the ten minute scheduling tolerance factor. Some example mission requirements are given below.

A propeller driven drone (100 knots) that must survey a division-sized front of ten miles, making two passes over this front, requires an illuminator time of 12 minutes. Adding the ten minute tolerance factor raises it to 22 minutes of dwell.

If the drone were jet propelled (400 knots) and tasked to cover the 100 mile front in the Iraqi war, extending from Kuwait City west into Iraq, its SAR receiver would operate for 15 minutes and a dwell time of 25 minutes would be called for.

A reasonable flight plan for a ground attack aircraft (420 knots) searching for mobile missile launchers, is that 15 minutes of fuel be allotted for search, and another 15 minutes be allotted for ground attack or self defense as the occasion requires. Adding the ten minute tolerance factor to the search time, yields a required dwell time of 25 minutes.

A B-52 (450 knots) at altitude, overflies the 200 mile illuminated region in 26 minutes. The SAR receiver is on for this time. This implies a dwell time requirement of 36 minutes.

The foregoing examples of operations are given to make plausible our assertion that a dwell time of 30 minutes over a theatre of operations is a reasonable value that could support widespread use of the satellite illumination. However, larger dwells would have military value.

GRAZING ANGLE REQUIREMENTS

The illuminator must illuminate ground targets for a time sufficient for airborne units to exploit the illumination. Terrain and trees may obscure the line-of-sight, but this may be overcome with a suitably large grazing angle. At large grazing angles (above 70 degrees) the line of sight is likely unobscured during the dwell. At smaller grazing angles the line of sight is obscured intermittently as the illuminator moves across the sky and the radar shadow from trees and terrain sweep across the object to be illuminated. The situation will dictate the minimum grazing angle that will "generally" be useable.

Satellites in geostationary orbits do not create moving shadows. All the shadows they generate are stationary. This introduces the possibility of enemy forces hiding in the shadows to avoid detection. However, it does not appear reasonable that all forces within the 200 mile illuminated spot would hide. The significance of the hiding tactic probably varies with the situation and generalizations cannot be made.

Intermittent illumination caused by the moving shadows of trees or terrain complicates the coordination problem for airborne platforms. Not only must their mission be scheduled within the dwell time window, but shadowing must also be considered. These complications can be avoided by requiring sufficiently large grazing angles that eliminate the obscuration possibilities.

There are some tactical missions for which target obscuration is not an issue. For example, when searching for air defense units, a small grazing angle (approximately one degree) may be adequate. This is because air defense units are sited to afford *themselves* visibility down to small grazing angles. By reciprocity, the satellite illuminator also has this advantage. Sea surveillance can also be conducted down to low grazing angles. We assume that a one degree angle suffices.

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Large regions of the world consist of deserts or grasslands. Obscuration is not a problem there. In summary, operation at a small grazing angle is possible in many applications. The illuminator dwell will not be interrupted by the moving shadows of trees or terrain.

Forested regions lead to a higher grazing angle requirement. Figure 3.1 is the basis for a ten degree minimum grazing angle[1]. The application is an unmanned air vehicle (UAV) operating over the Fulda Gap region in Germany. It was decided that ten degrees provided visibility to 80% of the road segments oriented within 20° of the radar line-of-sight. The region has curving roads with much tree cover.

A non-stationary satellite illuminator in the Fulda Gap application would illuminate each of the road segments for short periods during the beam dwell. To exploit this, one requires that the aircraft direct its SAR receiver antenna in a given direction for a longer time to capture all the transient illuminations of the various road segments.

Toyon Research has studied the mission of finding SS-25 batteries deployed along roads within the forests of the Soviet Union[2]. It was decided that 45 degrees represented a reasonably useful minimum grazing angle. A probability of 50% to 60% visibility to any road segment accrues at this angle, if the illuminator moves and the illuminator spot is stationary as the beam axis is steered through ninety degrees (Figure 3.2). However, the individual locations are illuminated for only short intervals of time during the beam dwell. Uninterrupted illumination occurs only at large grazing angles.

We conclude that there are no hard requirements on minimum grazing angle. We require that the satellite illuminator be designed operate down to one degree grazing angle. In the presence of tree or terrain obscurants, large grazing angles will provide uninterrupted illumination for the duration of the beam dwell and smaller angles will provide interrupted illumination. We will show illuminator performance for values of grazing angle between one and forty-five degrees.

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Schwartz et al. — *A Radar for Unmanned Air Vehicles*
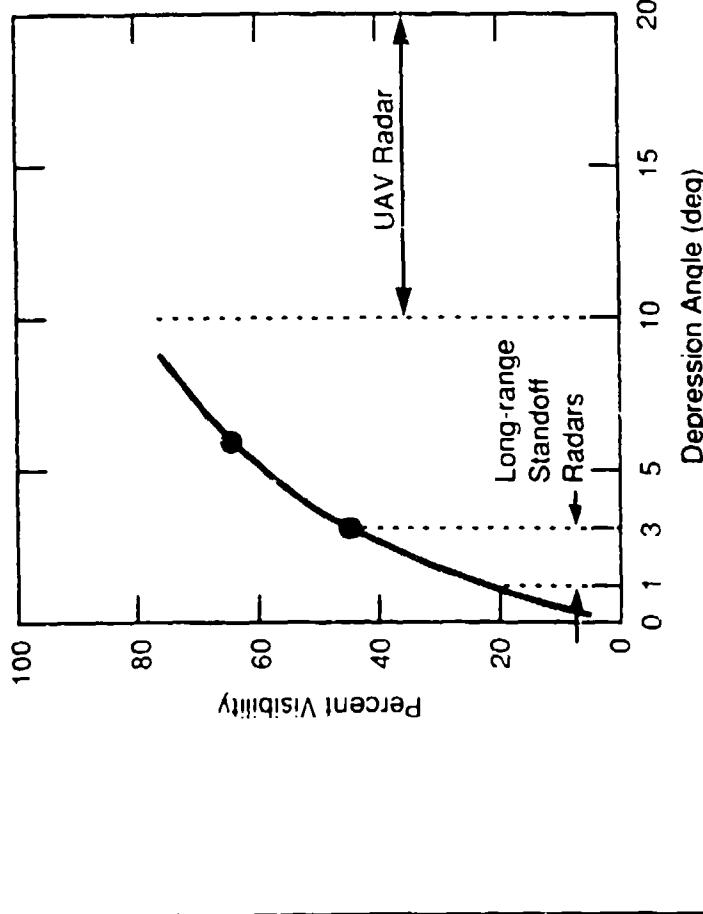
Figure 3.1. Visibility of moving vehicles on radial roads versus radar depression angle. Radial roads are those roads which are radial ($\pm$ 20") to the sensor. The depression angle is the angle of the radar's line of sight below a horizontal plane.

REVISIT FREQUENCY

Each point on earth within the latitude of an orbit's inclination passes through the orbital plane twice per day. Each passage is an opportunity for a revisit, but whether it occurs depends upon the position of the satellite at time of passage, the altitude of the satellite, and the field of regard of its sensor. It is possible to guarantee one revisit at each passage through the orbital plane. Later we will specify the orbital parameters of the illuminator to achieve this goal; here we discuss the requirement.

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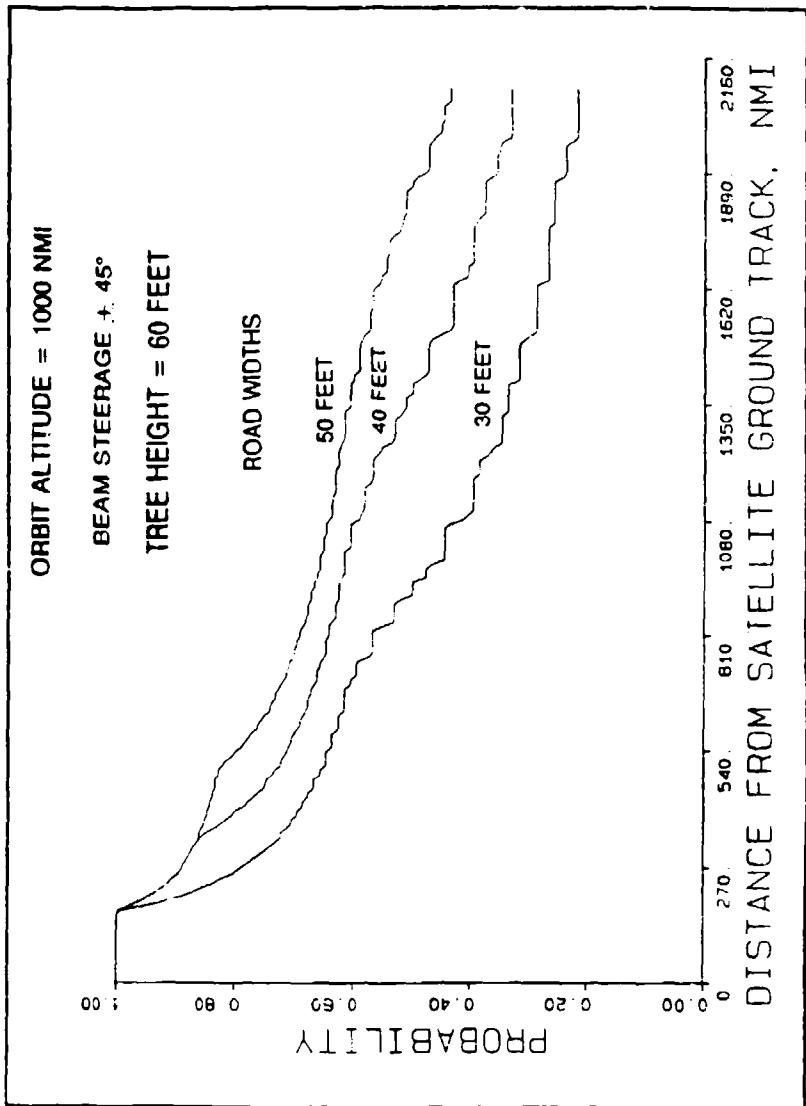
Figure 3.2. PCLOS in Wooded Areas

Where military operations can be timed to fit satellite revisit times, a revisit frequency of once per day might be adequate. However, this informs the enemy of possible times for the operation and allows him to prepare for it. In some cases this is not a factor, for example battle planning that occurs over a period of weeks.

A passive SAR capability aboard bombers, performing long range ground attack, would enable them to more carefully target their ordnance. These operations can timed to illuminator revisits of once or twice a day. UAVs performing reconnaissance using the passive SAR, can be launched to exploit the time when illumination is available.

For the support of fighter ground attack missions, a revisit frequency of two or three times per day may be required. This probably requires two or more illuminator satellites. The illuminator roles would support passive target acquisition and bomb damage assessment. By performing these functions passively, the SAR gives the aircraft the capability in overcast or foggy weather that IR/EO systems provide in clear weather or night operations.

Where the enemy determines the time of military operations, i.e., when he attacks, the illuminator function would have to be provided continuously. It could support early warning as well as the defense response. Navy anti-submarine surveillance, e.g., by an S-3 aircraft, is such an operation. By keeping the patrolling S-3 quiet, the submarine cannot dive or lower its periscope to avoid detection.

Geosynchronous orbits can provide continuous illuminator coverage, but lower equatorial altitudes are possible if using multiple satellites. Equatorial orbits cannot reach high latitudes and cannot be used where this is a requirement. For sea surveillance (one degree grazing angle requirement) an illuminator can reach 40 degrees latitude from one thousand miles altitude and 50 degrees from two thousand miles. This reach covers most of the worlds important sea surface.

FIELD OF REGARD REQUIREMENT

The antenna of the satellite illuminator is oriented downward to allow the beam to be steered equally well to all azimuths. The field-of-regard is the maximum angle (an elevation angle) between the antenna boresight and the beam steering direction. If the satellite illuminator in a given mission can operate down to grazing angles as small as one degree, then the field of regard of the antenna must be adequate to support this operation.

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Figure 3.3 illustrates the relation between field of regard, grazing angle, and satellite altitude. We require illuminator support of operations at one degree grazing angle. Above 530 miles satellite altitude, a sixty degree field of regard enables the satellite beam to reach down to one degree grazing angle. Sixty degrees is the largest practical field of regard; thus satellite altitudes should exceed 530 miles. A fifty degree field of regard requires satellite altitude exceeding 1100 miles.
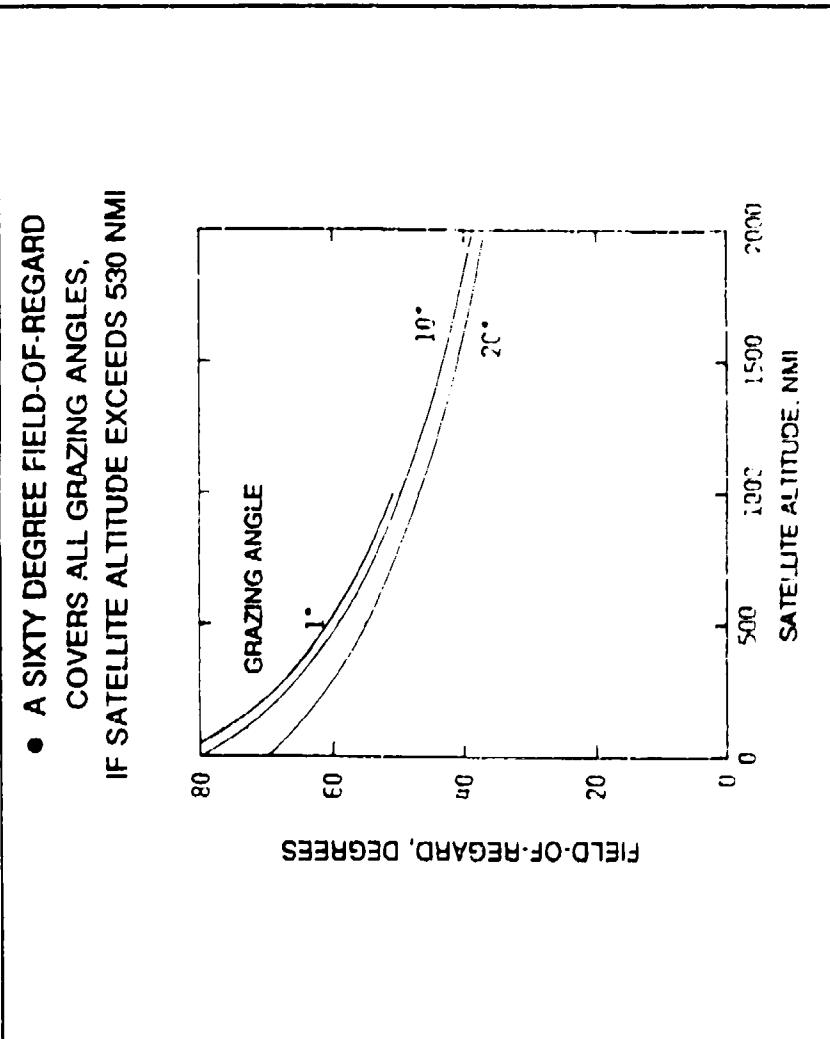

Figure 3.3. Relation Between Field of Regard and Grazing Angle

SUMMARY OF REQUIREMENTS

The constellation of illuminator satellites should meet these minimum requirements:

- Operation down to one degree grazing angle, and capability

  at higher angles.

- Two to four revisits per day
- 30 minutes dwell time per revisit
- Field of regard (<60°) and altitude (>530 nmi)
- Ground illumination spot of 200 mile diameter

In addition, cost constrains us to limit the constellation size to three. The use of a single satellite illuminator is preferred.

ILLUMINATOR CONSTELLATION DESIGN

We will develop the parameters of a satellite constellation of illuminators that meets the requirements specified earlier.

Next we will discuss the use of equatorial orbits. These possess the capability to provide continuous illuminator support; however, their operation is limited to lower latitudes. Later we will treat inclined orbits. They have the capability to cover any region of the world, but with the drawback of providing only finite dwell time at several revisits per day.

EQUATORIAL ORBITS

Non-Geosynchronous Altitudes

Figure 3.4 illustrates the latitude reach of a satellite in equatorial orbit. A satellite at 5000 mile altitude can reach an earth central angle (either latitudinal or longitudinal) of about 65 degrees when a one degree grazing angle is useable.
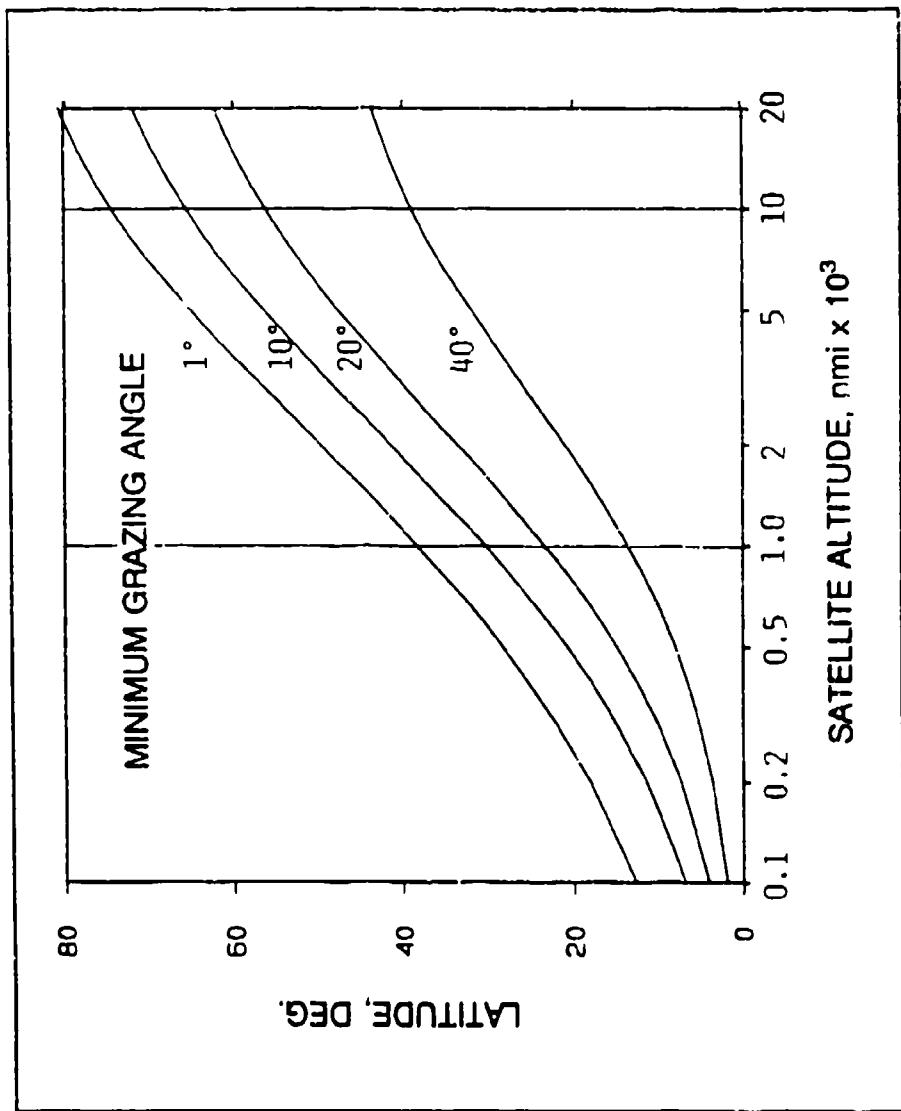

Figure 3.4. Latitude Reach of an Equatorial Orbit

Ten degree grazing angles require altitudes above 10000 miles. Thus three equatorial satellites equidistant in longitude and at these altitudes, will cover the equatorial region at all longitudes. Continuous coverage would be attained by transferring illumination responsibility among the satellites.

The satellites altitude should be high enough to provide adequate overlap in their coverage. The latitude reach of the satellites would vary from the 65 degree value at their longitude to some lesser value at longitudes midway between the satellites.

This coverage includes practically all of the important ocean surfaces of the world. For example, the Pacific Ocean extends to only 60 degrees north latitude. All of South America and Australia lie within 50 degrees south latitude. This constellation could support threat surveillance for the fleet by continuously illuminating a 100 mile radius around the fleet.

Geosynchronous Altitude

One satellite at geosynchronous altitude can cover almost half the world. Figure 3.4 shows the latitude coverage (interpretable also as longitude coverage) versus the minimum grazing angle desired. For ocean surveillance at a one degree grazing angle, all of the worlds bodies of water could be covered. Even with a ten degree grazing angle, coverage to seventy degrees is obtained. The single satellite could be moved to regions (longitudes) of interest and stationed for the duration of the requirement. Continuous support could be provided where needed. The beam (200 mile spot size) could be easily repositioned to illuminate any part of the theatre of operation.

The amount of fuel required to reposition a satellite is estimated in Figure 3.5. Repositioning would likely occur infrequently.
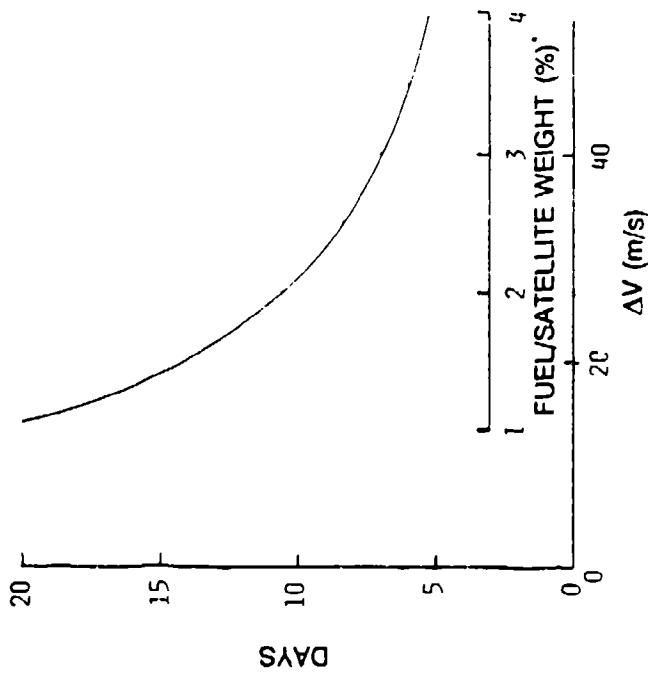
Figure 3.5. Approximate Time to Drift 90° Longitude From Geostationary Point

The potential for obscuration by terrain or trees increases as the illumination grazing angle decreases. Practically all of the inhabited land mass in the southern hemisphere lies at less than 45 degrees latitude and thus could be illuminated at grazing angles exceeding forty degrees. This provides good probability for clear line of sight.

Even in the northern hemisphere much of the conceivable future tactical operation areas (excluding the USSR) lie below fifty degrees latitude. Practically all of China and Mongolia lie below fifty degree latitude. These could be illuminated at grazing angles exceeding thirty degrees, thereby promising good probabilities for clear line of sight.

We conclude that a single satellite in geostationary orbit could serve much of our future tactical operations needs. It could be repositioned in longitude as needed. Its 200 mile wide beam could be repositioned as frequently as possible to serve the theatre commander.

Obscuration is the greatest problem at high northern latitudes because these are generally wooded up to sixty degrees latitude and require high illuminator grazing angles. Scenarios for military operation involve the USSR and northern Europe. Inclined illuminator orbits are required to support military operations in these latitudes, and elsewhere, when large grazing angles are required. We discuss inclined orbits in the following sections.

INCLINED ORBITS

Inclined orbits are necessary in the presence of tree and terrain obscuration. Inclined orbits allow satellites to overfly the region and illuminate it from a variety of angles — even overhead. The bistatic SAR can operate with the illuminator directly overhead the object being imaged. In this case the airborne receiver must be offset from the target to generate the usual side-looking geometry for the SAR receiver. The SAR receiver is also affected by obscurations but it generally has flexibility in positioning itself.

The movement of the illuminator across the sky causes the various target areas to be illuminated during some portion of the dwell. The airborne receiver platform must coordinate its operation with the times of illumination. This may be a problem for specific situations, and cannot be discussed generally. It is left for future study.

The following discusses how inclined orbits can meet the requirements listed in the Summary of Requirements. It is assumed that satellite orbits are below geosynchronous altitude.

Figure 3.6 illustrates the ground swath of an orbit on three consecutive passes. In this example the region between latitudes of about 50° to 65° is visited twice on each orbit and also on two or three successive orbits. Some regions at lower latitudes are skipped over by the satellite. To obtain overlapping coverage ensuring two revisits every 24 hours from
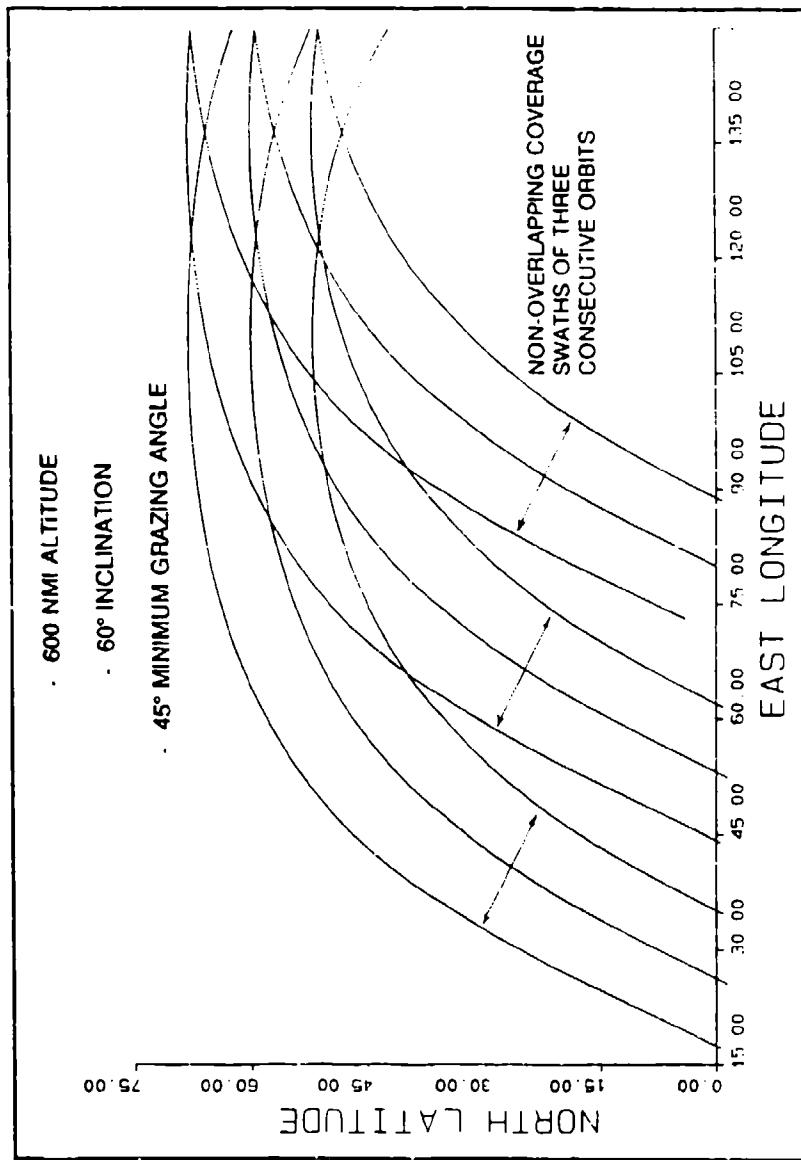
Figure 3.6. Example: Non-overlapping Satellite Coverage

each satellite, requires either that the grazing angle requirement be lowered or that the altitude of the satellite be raised. The two revisits are not equally spaced in time, except for areas near the equator.

In the following discussion a point is "visited" if the satellite dwells for a minimum period of time above some minimum grazing angle at that point. The dwell condition determines in Figure 3.7, the degree of overlap in the field of regard. A corollary to achieving this "visit" is that a point is always visited at least once, whenever passing through the orbital plane, that is, twice per 24 hours. This translates into a condition on satellite altitude for given minimum grazing angles. We assume circular orbits throughout.

- COVERAGE EVERY 12 HOURS PER SATELLITE
- ONE SATELLITE PER ORBITAL PLANE
- EQUAL SPACING BETWEEN RIGHT ASCENSIONS
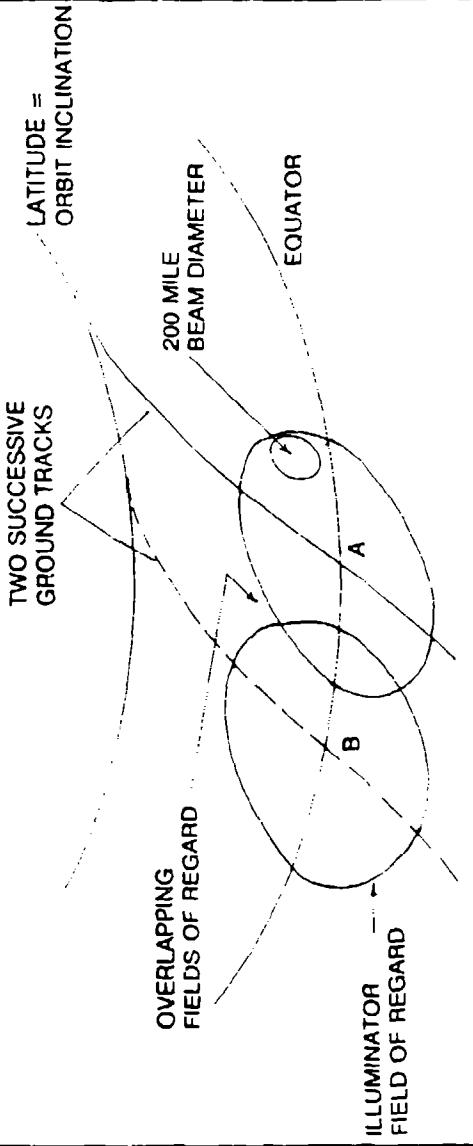
Figure 3.7. Inclined Orbit Option (Overlapping Adjacent Swaths)

The results of this analysis are shown in Figures 3.8, 3.9, and 3.10. These figures show the range of satellite altitudes where certain dwell times can be realized. We discuss Figure 3.8 in detail to illustrate all the figures. It assumes a ten degree minimum grazing angle. Three orbit inclinations are shown. The polar orbit covers all latitudes. With this orbit one can obtain at least a 30 minute dwell twice per day at every point on the earth, with satellite altitudes between 1800 miles and approximately 8000 miles. In fact a one hour dwell is realizable for altitudes between 4000 and 7000 miles. Note that operating in the Van Allen radiation belt will adversely affect satellite life (Figure 3.11).
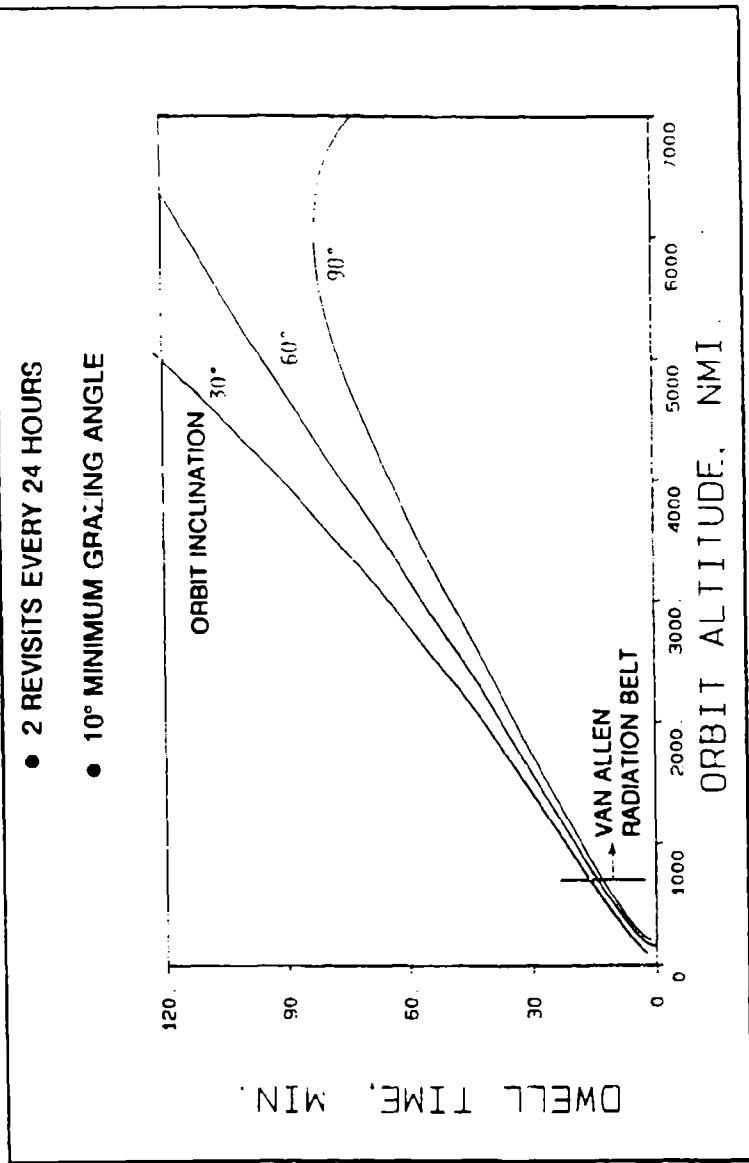
Figure 3.8. Illuminator Altitude for Minimum Required Dwell Time
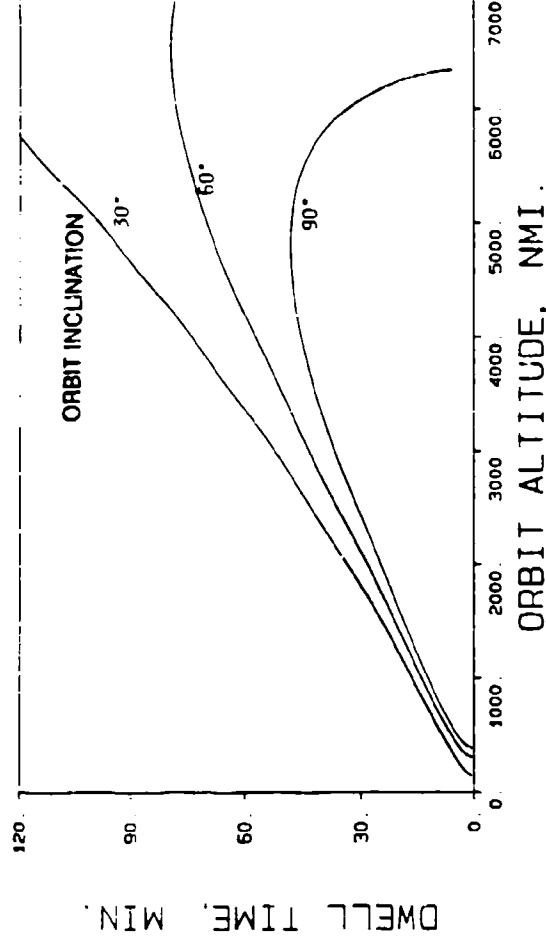
Figure 3.9. Illuminator Altitude for Minimum Required Dwell Time

Figures 3.8, 3.9, and 3.10 illustrate the progressive constriction caused by requiring larger grazing angles. At twenty degrees one can provide 30 minute dwell to all points on earth with a polar orbit. One hour dwell can be provided to sixty degree latitudes with a sixty degree inclined orbit. Actually, the one hour dwell is realized a few degrees beyond the latitude of the orbits inclination.

Figure 3.10 shows that with thirty degrees grazing angle the 30 minute dwell can no longer be obtained in polar orbits, but can be obtained with inclined orbits at least up to sixty degree latitude. Satellite altitudes must lie between 3100 and 5800 miles. These orbits can provide 30 minute dwell for grazing angles up to about 35 degrees.
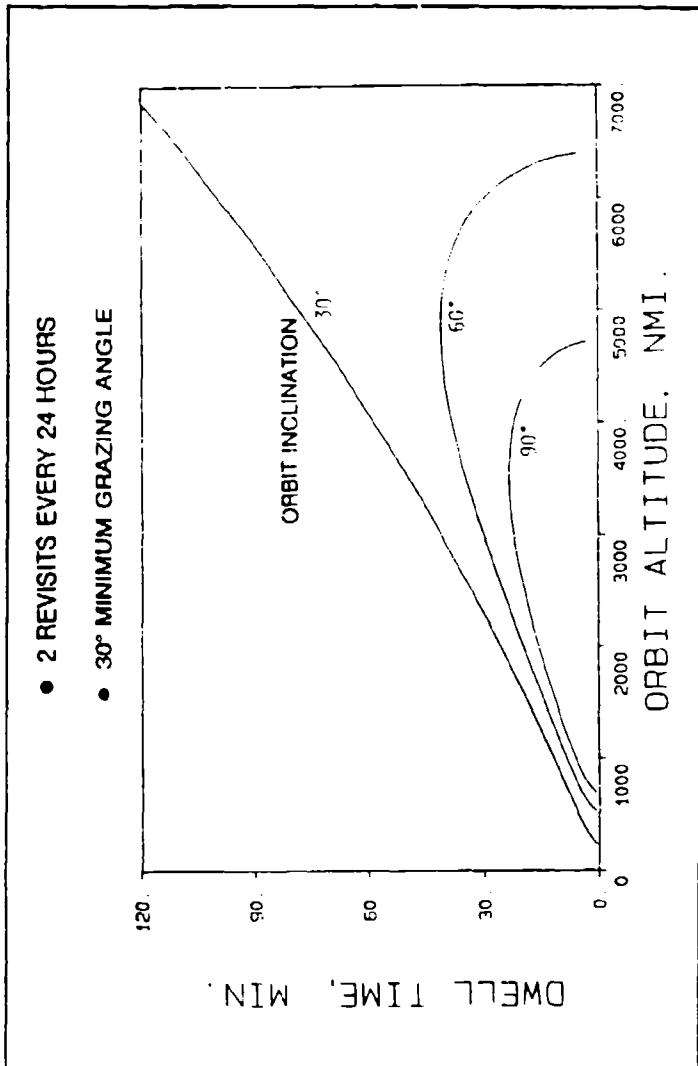
Figure 3.10. Illuminator Altitude for Minimum Required Dwell Time

Dwell time falls off rapidly for higher grazing angles (charts not shown). The sixty degree inclined orbit achieves only about 15 minutes of dwell with a 40 degree grazing angle and negligible dwell time (4 minutes) at 45 degree grazing angle.

The limiting grazing angles and minimal dwell times are achieved at points midway between the ground track of successive orbits. Larger grazing angles or longer dwell accrues to areas closer to the orbital plane.

We conclude that circular orbits can provide the requisite 30 minute dwell at up to 60 degree latitudes provided grazing angles down to thirty degrees are useable. Each satellite will generate two visits per day. However, they will not

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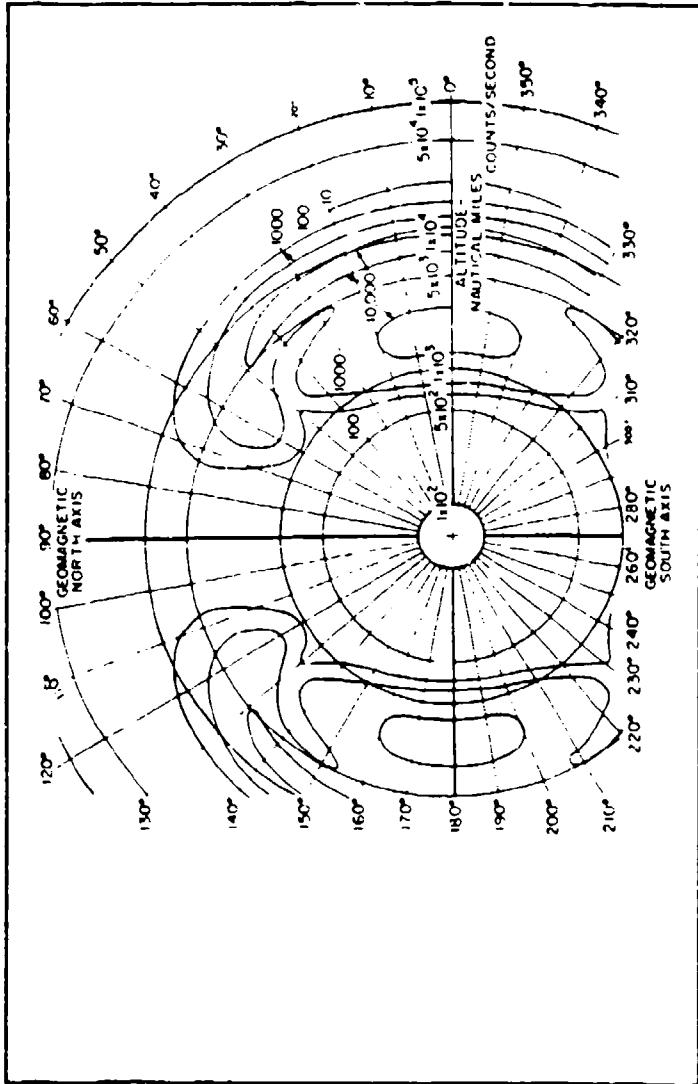
Figure 3.11. Van Allen Radiation Belt

be evenly spaced. More visits per day are generated by adding more satellites, one per orbital plane, and evenly spacing the right ascensions of their ascending nodes.

To achieve reasonable dwell at grazing angles of 45 degrees, requires the relaxation of some of the conditions. By dropping the requirement for two revisits every 24 hours, longer dwells at high grazing angles may be obtained. This has not been quantified.

REQUIREMENTS ON THE AIRBORNE SAR RECEIVER

We discuss requirements on receiver image resolution and sensitivity. Cross range and down range resolution generally differ, but we neglect that detail. The objective of image resolution can in broad terms either be:

- To detect the presence of objects
- To identify the type of object
- To characterize the state of the object

These objectives are listed in order of increasing required resolution.

By receiver sensitivity is meant the radar cross-section per resolution cell that the SAR should detect (with a given signal-to-noise ratio). RCS values differ markedly among pixels — one pixel may encompass a corner reflector where another pixel encompasses a flat planar surface. The relative RCS values may change according to the look orientation at the entire object.

The number of pixels that must be detected depends upon the imaging objective discussed above. As one requires that more pixels be detected, one requires more sensitivity because a larger group of pixels will likely include some fainter ones.

The resolution and the number of detected pixels required to detect, identify, or characterize an object can only be determined empirically, and whether a given military operation requires identification or characterization requires a level of detailed analysis beyond the scope of the present work. Thus, we cannot generate detailed requirements. We merely hope to illustrate their general order of magnitude.

RESOLUTION

Table 1 presents the definitions for image interpretability according to the National Radar Interpretability Scale (NRIS). They show ten levels, some of which must be qualified further by a probability for attainment. Based on the size of significant target features, we have estimated the resolution required to interpret a given object at each of the levels. The results are summarized in Figure 3.12.

An NRIS level of 4 would appear to represent the least useable capability for general tactical or strategic surveillance. This permits one to recognize the general type of object. An NRIS capability of 6 allows one to begin characterizing the object.

We estimate that detection/counting of ground vehicles requires five to ten foot resolution and ground target classification requires one to two foot resolution. Larger targets, such as aircraft, may permit relaxed resolution requirements.

SENSITIVITY

For a complex shaped object, the RCS of the entire body (the narrowband RCS) equals the sum of the average RCS of the pixels (the wideband RCS)[3]. Narrowband RCS values are known for a wide class of objects. Table 2 lists some representative cross-sections.

The RCS values in the table exclude major speculars in the pattern. In that sense the values are typical of most orientations of viewing.

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Table 1. National Radar Interpretability Scale (NRIS)

SCALE LEVEL[*]	TASK	EXAMPLES	
		GROUND VEHICLES	AIRCRAFT
9	ID Model Look-alikes	M-48 Versus M-551	F102 Versus F106
8	ID Model/Function	Tank Versus SP	F4 Versus A4
7	ID Specific Function/ Configuration	AFV Versus Combat Spot	Swept Versus Delta Wing
6	Classify General Function/ Configuration	Tracked Versus Wheeled	Straight Versus Swept or Delta Wing
5	Classify Size/Type	L/M/S	L/M/S; Fixed Wing Versus Rotary
4	Classify by Object Type	Vehicle	Aircraft
3	Detect Activity	Field Deployed Units	Flight Line Activity (TBR)
2	Count Objects	Vehicles $\pm$ 50%	Small Aircraft $\pm$ 50%
1	Detect Facilities	Motor Pools	Hangars/Buildings
0	Unusable	Unusable	Unusable

[*] Defined for levels 4 - 9 as the level of performance which can be achieved at a known installation for most (~80%) of the objects present.

Source: General Research Corporation
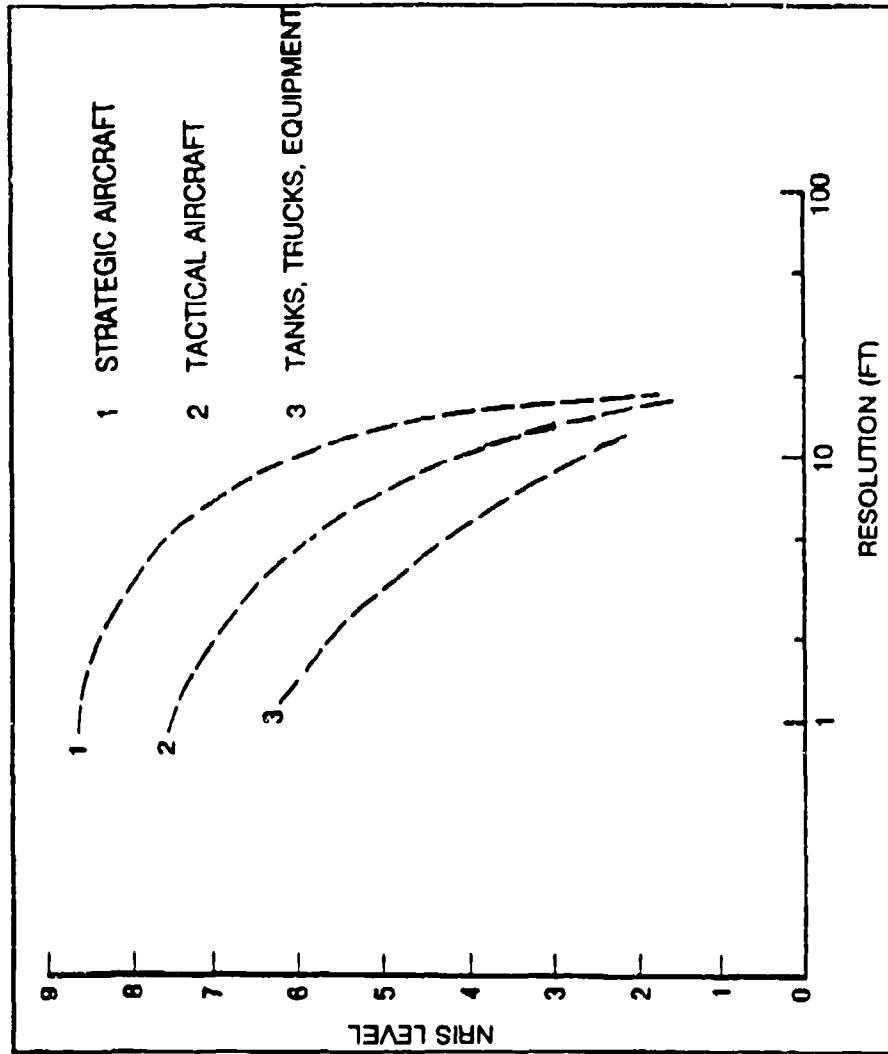
Figure 3.12. Image Interpretability Versus Resolution

Per pixel RCS values must be less than the narrow band (whole body) value. The distribution of pixel RCS values for objects varies by object type, but some generalizations are possible[4]. If all pixels were equally bright, they would divide the whole body RCS (square meters) equally among themselves. The appropriate SAR sensitivity criterion in this case is average value — the whole body RCS divided by the number of pixels on the object. This criterion integrates the object's projected area (in the image projection plane), the SAR resolution, and the objects whole body RCS. This situation

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Table 2. Selected Narrow Band Radar Cross-Sections

OBJECT	TYPICAL RCS	PARAMETERS[*]
C-54 Aircraft	15 dBsm	X-band, H/V
T-38 Aircraft	0 dBsm	X-band, H/V
Teledyne Ryan Firebee	-3 dBsm	X-band, H
Automobile	20 dBsm	X-band, H/V
Pickup Truck	23 dBsm	X-band, H/V
URBAN AREAS ($\sigma°$) 20° Grazing Angle	-20 dB	S-band, H
	-8 dB	C-band, H
	-3 dB	X-band, H

circumvents the issue of how many pixels have to be detected in order to identify or characterize the object, because all pixels are detected if one is.

In practice pixels are not equally bright. In fact their range of brightness for common objects covers 20 to 50 dB. If their RCS values were linearly distributed over the range of values (in square meters), the average value would equate to

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[*] H/V signify horizontal (HH) or vertical polarization (VV).

the median pixel; that is half of the pixels would have RCS values greater than the average. One guesses that the detection of half the pixels on target might suffice to achieve any imaging objective. Thus, the average RCS value in this case is not a patently unreasonable goal for receiver sensitivity.

The average RCS value is also a reasonable goal for all symmetric distributions, e.g., the normal distribution. Half of the pixels have RCS values greater than the average.

If pixel RCS values are distributed according to the exponential distribution ", then the RCS values become concentrated in a few pixels. The middle pixel in the count of target pixels would have an RCS value less than the average. That is, the average RCS criterion would image less than half of the target pixels. Figure 3.13 illustrates the fraction of pixels that have RCS values exceeding the average, assuming the exponential distribution. This fraction exceeds 20% for a wide range of circumstances. This is not on the surface an unreasonable fraction for large objects; however, a criterion of a minimum number of detected pixels might be more suitable for small objects.

We have not examined the RCS distribution of pixels of specific objects nor the number required to be detected to accomplish the imaging objective. Therefore, we simply rely upon the average RCS criterion.

We illustrate this criterion with the objects in Table 2. Assume the automobile to be 2 meters wide by 4 meters long when projected in the image plane. A SAR resolution of one meter results in eight pixels on target and the average pixel RCS is 12.5 square meters. Likely 2-3 pixels exceed this average RCS and would be visible. This is probably

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" Wehner, op. cit., uses this hypothesis. Section 7.15 evaluates the fraction of targets elements that must be visible (detected).

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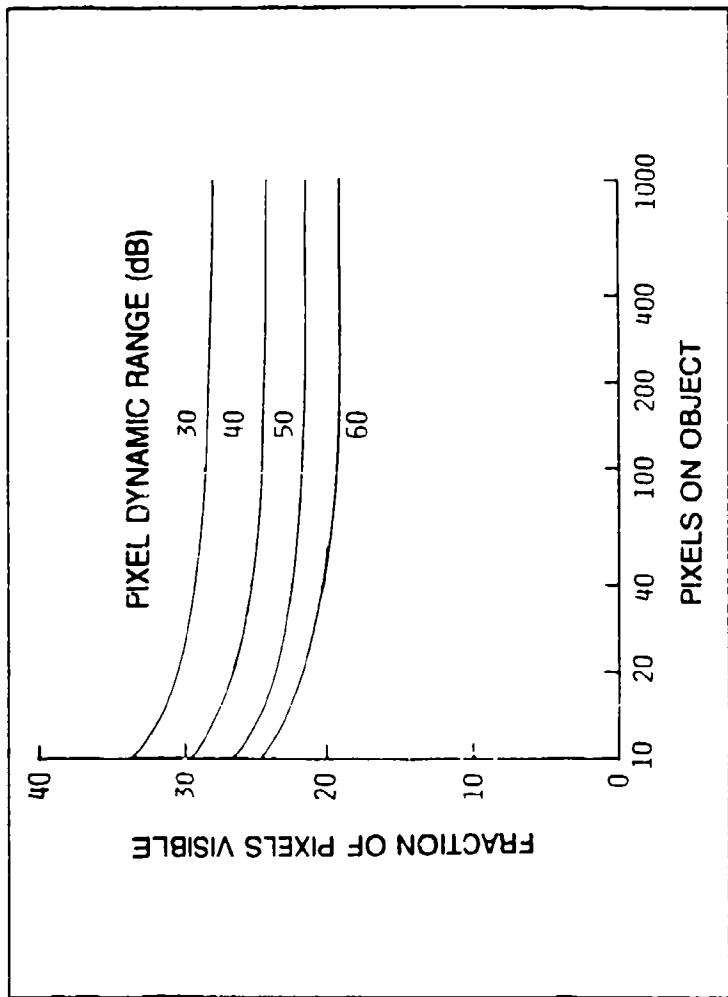
Figure 3.13. Performance of Average Pixel RCS Criterion

insufficient to identify this small object and one would require more resolution and receiver sensitivity. At one-half meter resolution, there are 32 pixels on target and the average pixel RCS is 3.1 square meters. Likely 6-7 pixels are larger than 3 square meters. At this resolution the object could be identified. Probably, more pixels would have to be visible and more sensitivity required to characterize the automobile.

The pickup truck with dimensions 2 x 5 meters would yield a per pixel RCS of 20 square meters at one meter resolution and 5 square meters at one-half meter resolution. About 8-10 pixels would be visible at the higher resolution and sensitivity. This likely suffices for identification and may suffice for characterization.

The aircraft in Table 2 would probably have average per pixel RCS values less than one square meter.

Urban clutter at X-band represents an average RCS of 0.5 square meter at one meter resolution, and 0.125 square meter at one-half square meter resolution. The ability to image this clutter would include the ability to image the other objects in Table 2. We conclude that 1/8 square meter (-9 dBsm) per pixel is a reasonable goal for imaging land-based objects in order to characterize them.

RECEIVER DESIGNS

Resolution

To illustrate the attainable radar performance, we have assumed the following values:

Integration time	= 10 seconds
Bandwidth	= 500 mHz
Noise figure	= 4 dB
System losses	= 10 dB
Required S/N ratio	= 13 dB
Receiver platform velocity	= 200 m/s
Receiver platform altitude	= 10 km

The integration time (array time) given above represents the maximum value that is felt to be currently achievable. The limiting factor is the stability of the local oscillator. This time represents the dwell time of the receiver beam, when operating in the spotlight mode. For swath mode operation, the azimuthal beamwidth of the receiver has to be made compatible with the dwell time. The numbers are reasonable. For example, for imaging a swath at 30 kilometer range, one requires a beam width of 2 kilometers on the ground and this represents a 3.8 degree beam.

The resolution attainable within the receiver beam depends upon its platform velocity and the speed and direction of travel of the satellite illuminator. A series of resolution maps have been prepared and are illustrated elsewhere in this report. At low satellite altitudes the motion of the satellite dominates whereas for geostationary satellites the motion of the receiver platform dominates. Figure 3.14 attempts to summarize this situation by showing the average capability for a
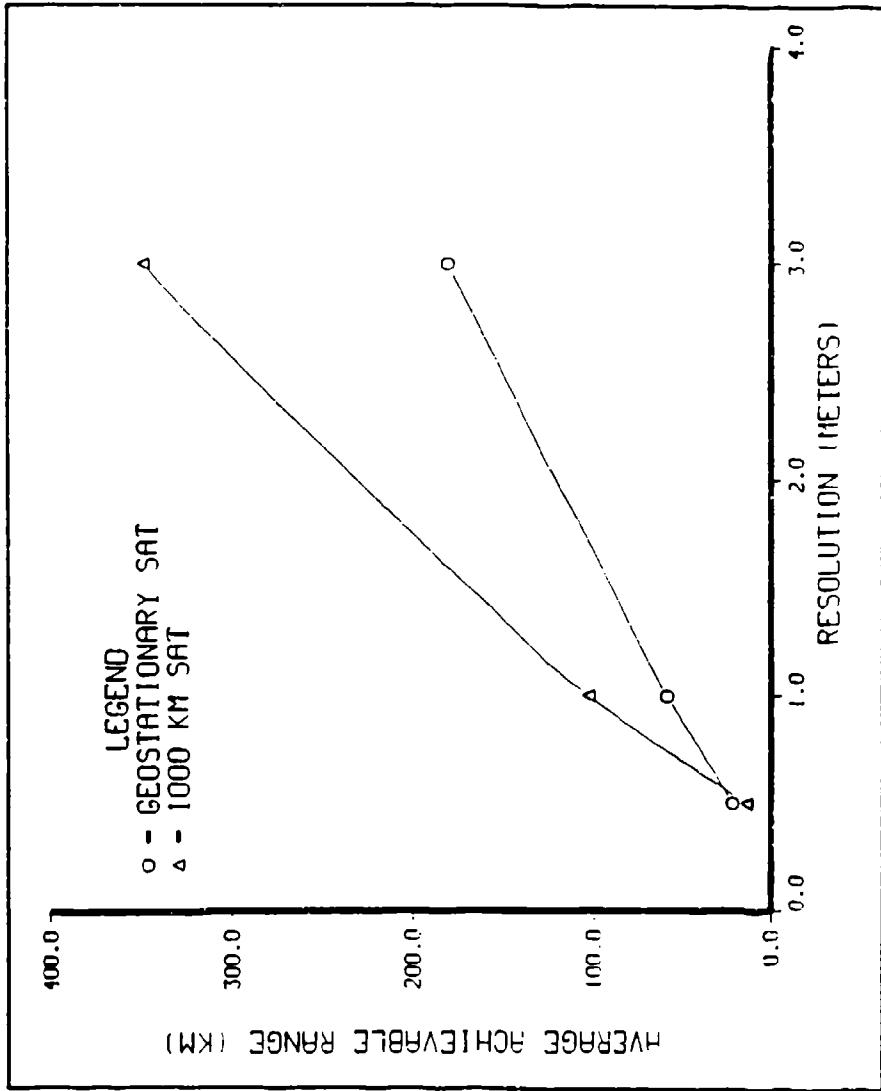

Figure 3.14. Receive Range Versus Resolution

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low altitude and a geostationary satellite. For the low altitude (LEO) satellite, the average is taken over a variety of satellite positions and direction of travel. For the geostationary satellite, the average is taken over a variety of receiver locations (lat, lon) relative to the satellite location. Grazing angle limits are not considered.

Object identification is possible at 1.5 to 3 meters (five to ten feet) resolution. Using a two meter typical value, Figure 3.13 indicates that this resolution can be obtained out to 100 kilometers for a geostationary satellite, and 220 kilometers for a LEO satellite. One meter resolution may suffice for object characterization, and it is achieved at a useful range of 50-100 kilometers.

These range figures merely quantify the average standoff range capability of the airborne receiver platform from the area to be imaged. However, there is no hard requirement on this standoff range. Thus, even the shortest 50 kilometer range mentioned above is useable in some scenarios.

Figures 3.15 and 3.16 illustrate the maximum and minimum values associated with the average value plotted in Figure 3.14. The LEO satellite shows wide variance in the range performance at all resolution values. The variability of the performance may render impractical the use of a LEO satellite illuminator. The receiver platform would have to know where his beam could be pointed to achieve the desired resolution. We have not investigated whether a simple algorithm exists to guide receiver beam pointing.

Figure 3.16 shows the case for a geostationary illuminator satellite. There is much less variability of performance. One meter resolution can usually be achieved out to a 50 kilometer range.
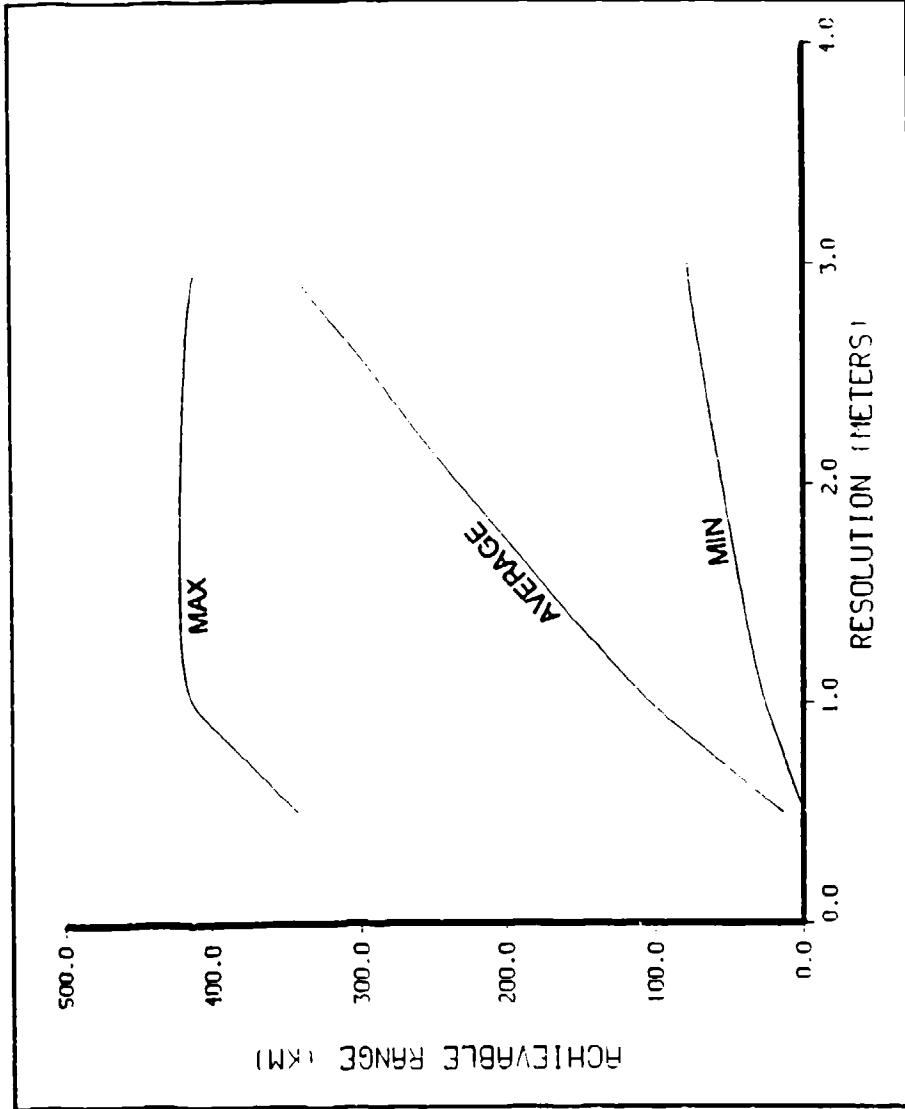
Figure 3.15. Resolution Performance (1000 Kilometer Satellite)

SENSITIVITY

The maximum useable range for imaging depends upon the sensitivity of the receiver as well as the resolution required. The preceding section discussed the resolution impacts. Here we discuss the sensitivity of the receiver.
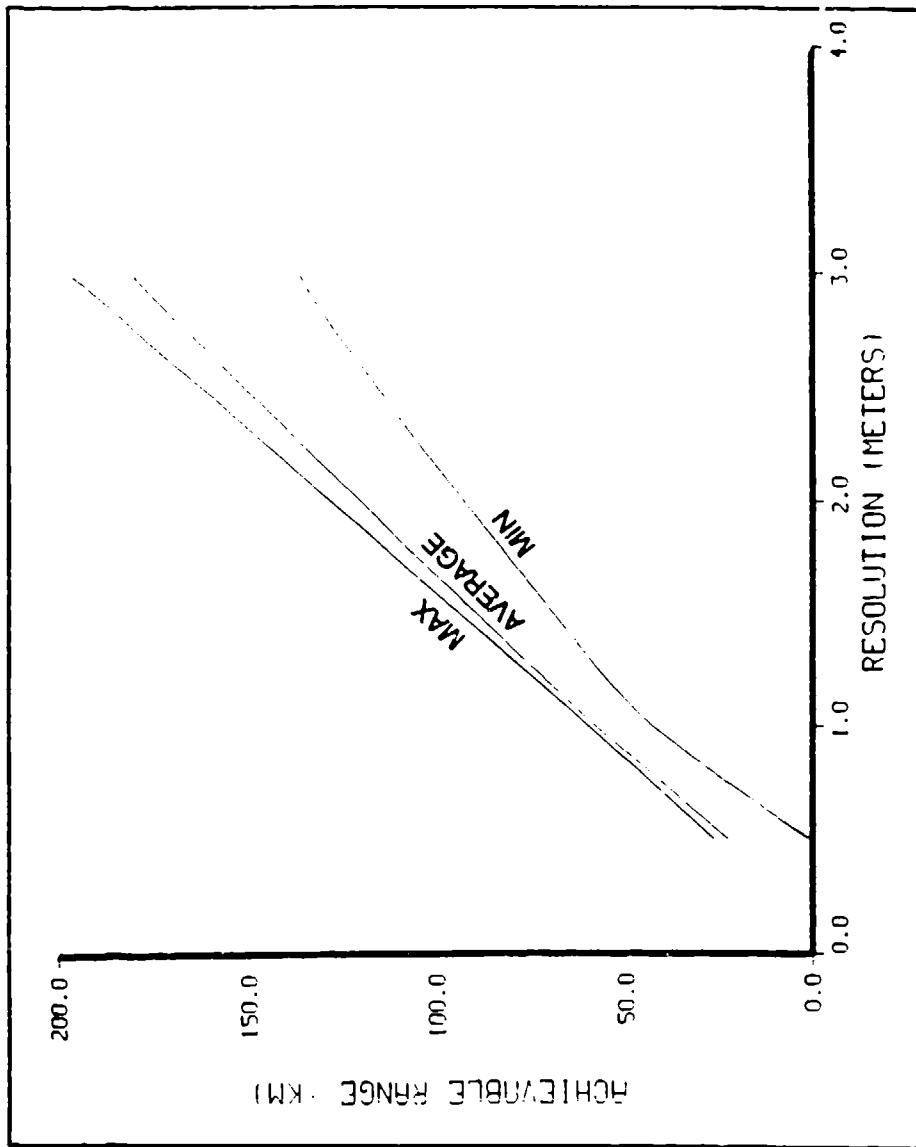
Figure 3.16. Resolution Performance (Geostationary Satellite)

Figure 3.17 summarizes the analysis for two cases, differing by the size of the receiver antenna. If the -9 dBsm criterion is used at 1/2 meter resolution, then 15 to 50 kilometer range is possible. The characterization of most objects is attainable at this sensitivity level.

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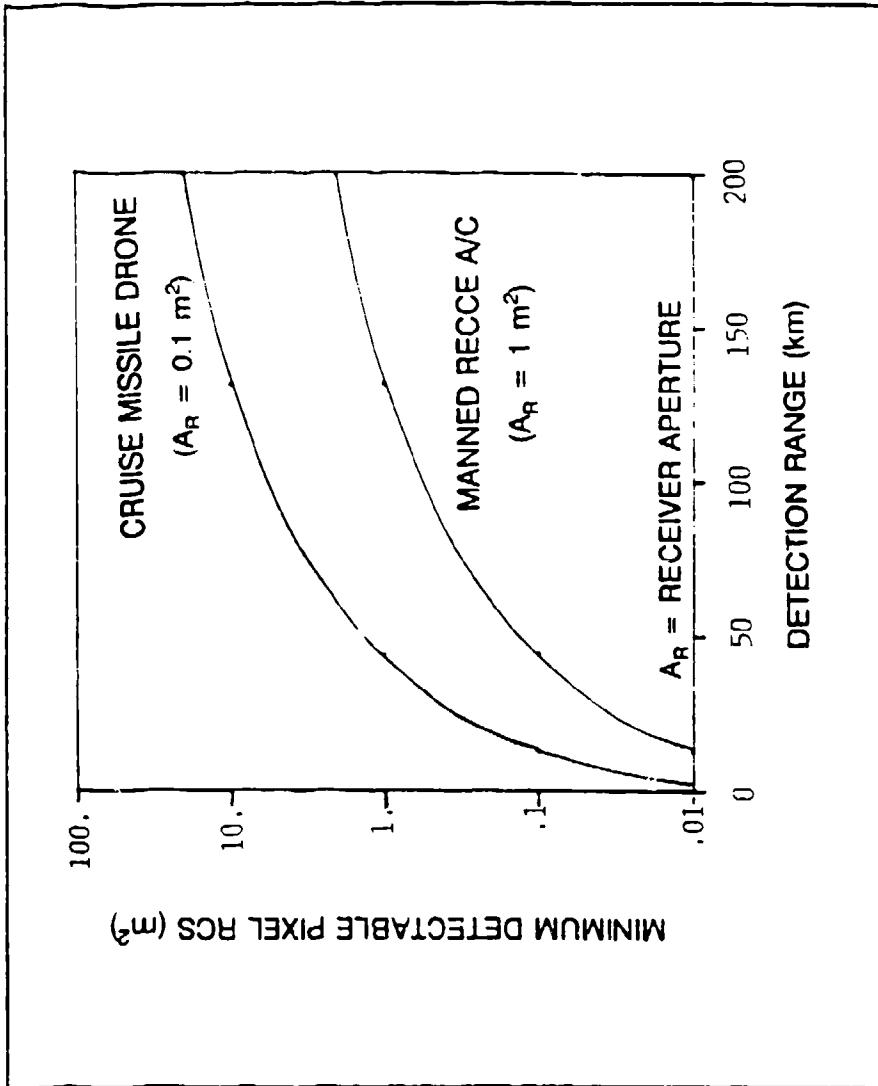
Figure 3.17. Detection Performance

Earlier we indicated that a 1/2 square meter resolution and one square meter sensitivity might suffice for many land vehicles. Figure 3.17 indicates that one expects imaging ranges of 50 to 130 kilometers in this case.

These range values may suffice for different applications. Drone cruise missiles generally overfly the region to be mapped; thus, they can tolerate shorter imaging ranges. Manned reconnaissance aircraft may be forced to standoff from

the area to be imaged, and will require longer ranges. The range capabilities derived from Figure 3.16 are roughly suitable for tactical application.

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3. Andrew L. Moffett, A Statistical Description of Radar Cross Section, John Wiley and Sons, 1989, Paragraph 12-1.

4. Donald R Wehner, High Resolution Radar, Artech House, Inc. 1987.

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CHAPTER 4
FAST LAUNCH ACTIVE RADAR EXPENDABLE (FLARE) CONCEPT

M.P. Grace

INTRODUCTION

In the current Desert Storm scenario, Iraq's mobile tactical ballistic missiles (e.g., SCUDs) have proven to be a potent political, if not military, threat. Nevertheless, it is the military's job to find and eliminate these targets. While the Patriot missile system has done an admirable job at terminal defense against the SCUD missiles, military command recognizes that the limited number of SCUD launchers are the Achilles heel of the SCUD threat; if these launchers could be located and destroyed, the threat of the hundreds of missiles postulated to still be available to Saddam Hussein would be nullified.

Even with fairly accurate launch-point estimation from surveillance satellites such as DSP, the launchers have proven to be difficult to target with conventional weapons. They can be deployed beyond the horizon of stand-off surveillance/tracking platforms such as AWACS or JSTARS. Because the launchers are designed to quickly evacuate after the missile is fired, they can move to a remote hiding spot long before an attack plane can arrive at the estimated launch point.

Consider the timeline as reported in Aviation Week & Space Technology and depicted in Figure 4.1. A SCUD missile is launched at some time chosen by the Iraqis. Once the missile is launched, the launcher may begin tearing down in preparation to move. Within a minute, a DSP IR surveillance satellite views the hot plume of the burning rocket as it rises above the clouds and low atmosphere. The sensor outputs are immediately sent to ground stations in the U.S. and Australia. Within five minutes, the SCUD launch detection is verified, the launch and impact points are estimated, and the notification is relayed back to tactical command and to terminal defense sites. At this point in time, F-15E attack planes may be directed to fly to the estimated launch point, to find the launchers, and to destroy them.

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CONUS

COMMUNICATION SATELLITE

COLLECTION SATELLITE

LAUNCH POINT

IRAQ

INTELLIGENCE GROUND SITE

TERMINAL DEFENSES

* 1) T=0 MIN., SCUD MISSILE IS LAUNCHED, TEL TEARDOWN BEGINS
2) T<1 MIN., DSP SATELLITE DETECTS LAUNCH, DATA SENT TO CONUS
3) T=5 MIN., TERMINAL DEFENSE, TACTICAL COMMAND NOTIFIED
4) T=5+ MIN., F-15 ON ALERT/CAP LEAVES TO FIND TEL
5) T=XX MIN., TEL EITHER A) STAYS PUT & COVERS UP
                         B) GETS UP & MOVE
                         C) GETS UP, MOVES, & HIDES

*Aviation Week and Space Technology, January 21, 1991, page 60

Figure 4.1. Desert Storm Mission: Find SCUD Launcher

If the launcher has the capability to move in virtually any direction, then the target location uncertainty region which the F-15 must search grows as the square of time after teardown. By the time the attack plane arrives, the possible region containing the target can be huge compared with the attack plane's capability to search out ground targets (the searched region grows linearly with time after the F-15 arrives). This problem is shown graphically in Figure 4.2. The assumption here is that the launcher can move in any direction from the launch point at an average velocity of 25 kts. In reality, the launcher may move slower if it travels off-road or much faster if it travels on roads. Travelling faster down roads is not necessarily better because if the attacker knows the launcher is travelling on roads, his search can efficiently be confined to the roads.
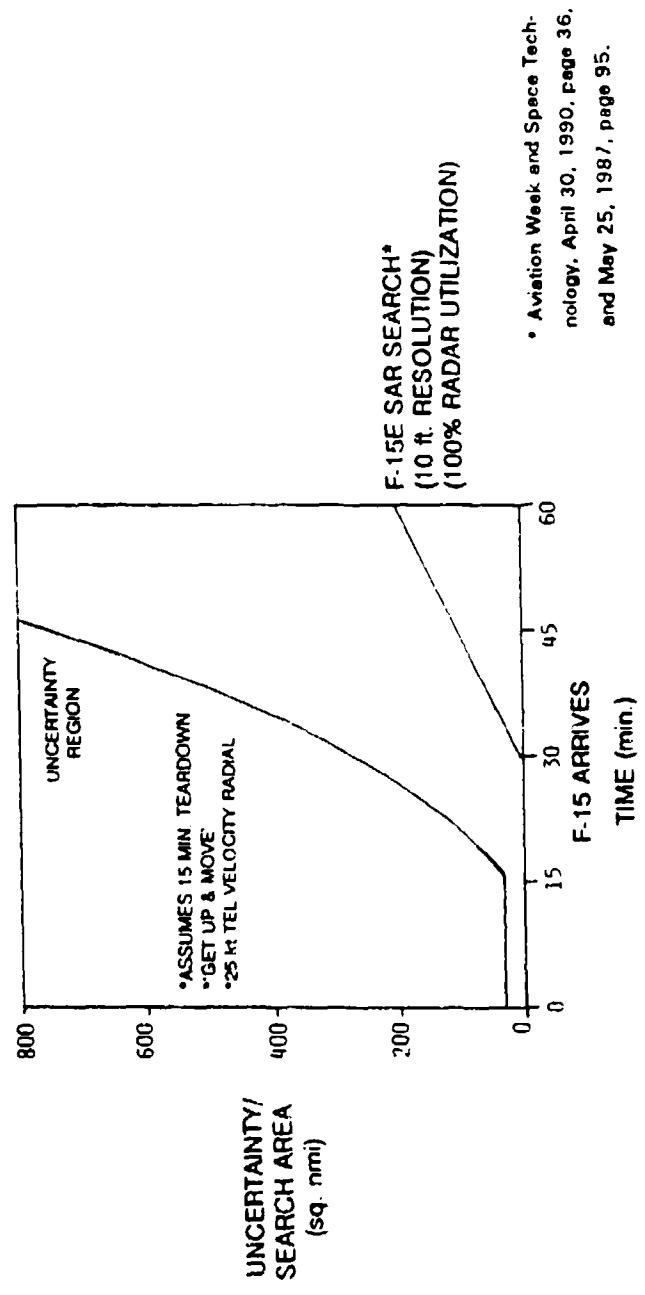
Figure 4.2. Uncertainty Growth vs. Search Rate Capability

CONCEPT DESCRIPTION

Fast-Launch Autonomous Radar Expendable (FLARE) is envisioned as a small radar promptly deployed over the estimated launch point using a tactical ballistic missile (TBM). This FLARE would maintain surveillance of ground targets leaving the suspected launch region out to a range of between 30 - 60 nmi until the airbreathing attacker (e.g., F-15E) arrives (about 30 minutes to an hour). The FLARE would aid in finding relocatable tactical missile launchers (e.g., SCUDs) by tracking anything that moves away from the launch point until the attacker arrives in the vicinity. After arriving, the F-15 could quickly examine each of the movers with a discrimination sensor (high resolution SAR or LANTIRN) to find the target if it had moved. If the target had not moved, the F-15 could then return to search the original launch point uncertainty area to find the target. Figure 4.3 depicts a parachuted FLARE deployed from a TBM.

(1) FLARE DETECTS & REPORTS MOVERS TO F-15 VIA AWACS

(2) F-15 ARRIVES, INSPECTS MOVERS, ATTACKS TARGET IF FOUND, OTHERWISE RETURNS TO SEARCH DSP CUE AREA
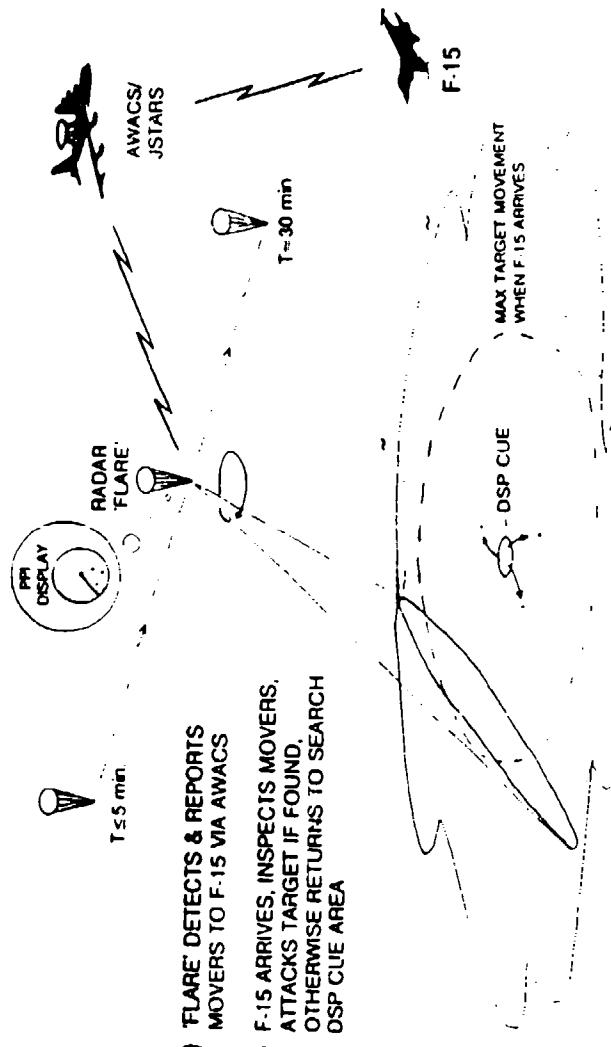
Figure 4.3. Prompt MTI Surveillance Minimizes F-15 Search

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The utility of the FLARE is to limit the growth of the launcher location uncertainty region to an absolute minimum. In addition to benefitting from a more efficient search process, the attacker has minimal exposure to anti-radiation missiles (ARMs) and jamming, and can utilize more of its radar resources for maintaining surveillance for enemy aircraft.

It may be possible to utilize the FLARE as an illuminator for bistatic operation. As a passive receiver, the attacker would benefit from further enhanced survivability from ARMs, and resistance to jamming.

Because the radar performs a single function, it can be made small and lightweight (and, ideally, cheap). An example of such a radar payload has been built and tested by MIT Lincoln Laboratories under the DARPA-sponsored AMBER UAV program. Some of the design details are listed in Tables 4.1 and 4.2 below[1]. The AMBER radar's range performance may be

Table 4.1. UAV Radar Weight and Power Budget

	Weight	Power
Radar		
Transmitter	21	355
Receiver and exciter	10	95
Processor	55	400
Antenna system	14	75
Cables and connectors	10	25
	110 lb	950 W
Support Equipment		
Inertial Navigation System (including heat sink)	17	50
Data link	12	185
Altimeter and GPS receiver	9	20
Support structure	25	n/a
Cooling fans	2	150
	65 lb	405 W
Total	175 lb	1355 W

i   C. E. Schwartz, T. G. Bryant, J. H. Cosgrove, G. B. Morse, and J. K. Noonan, "A Radar for Unmanned Air Vehicles," The Lincoln Laboratory Journal, Vol. 3, No. 1 (1990).

Table 4.2. UAV Radar Parameters

Radar type:	coherent-pulse Doppler
Frequency:	Ku-band
RF bandwidth (instantaneous):	10 MHz
Receiver noise figure:	7 dB
PRF (variable):	3 to 10 kHz
Range resolution:	15, 30, and 50 m
Linear dynamic range:	40 dB minimum
A/D quantization of I/Q video:	8 bits/channel
Antenna reflector type:	parabolic 18 in x 8 in
Rotary joints:	azimuth and elevation
Elevation pattern:	cosecant squared
Azimuth beamwidth:	3°
Scan speed (variable):	0°/s to 48°/s
Azimuth sidelobes:	−28 dB (maximum), −35 dB (average)
Peak gain:	30 dBi
Polarization:	horizontal

too limited but the design is representative of the class of radar required for this mission. Other radar candidates include helicopter radars or perhaps a concept-unique design.

Several deployment schemes for providing the required 30 to 60 minutes of "hang-time" for the radar are possible. Figure 4.4 shows the descent profile of a parachuted payload. A simple parachute can achieve the "minimum" 30 minute hang-time as shown in the descent profile below. Parachutes are lightweight, low-cost, and easily deployed, but they have disadvantages as well: time aloft above a 10 kft altitude (desired for long range coverage and for minimizing vulnerability to small air-defense systems) is limited, even with high altitude deployment; wind drift in certain geographic areas could be a
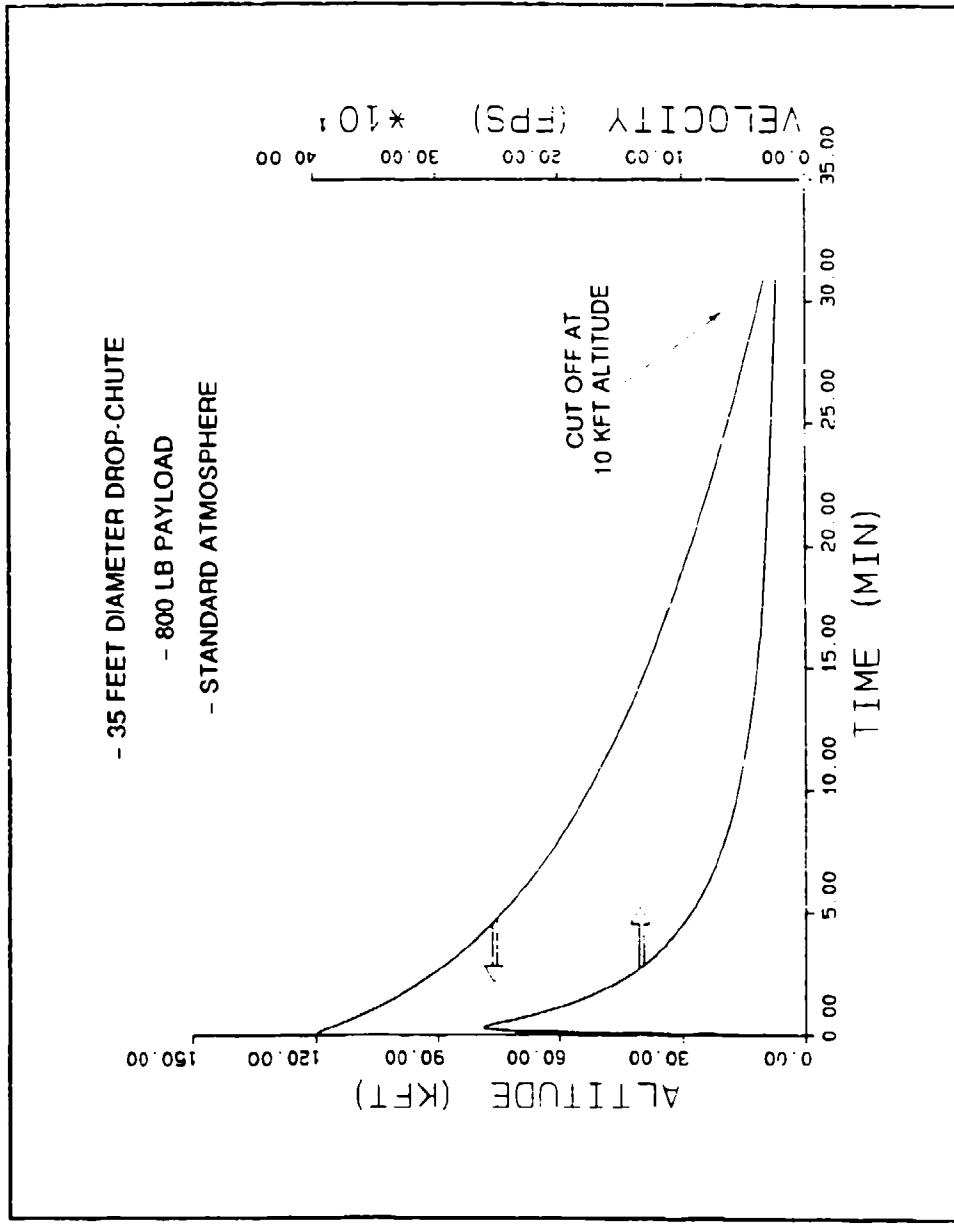
Figure 4.4. Descent of a Payload with Parachute

problem; they may be very difficult to recover over enemy territory. Other possibilities including parafoils, balloons, fixed-winged vehicles (such as AMBER UAV, shown in Figure 4.5[1]), and rotating-wing vehicles may offer improved performance at the cost of increased complexity, weight, and cost.
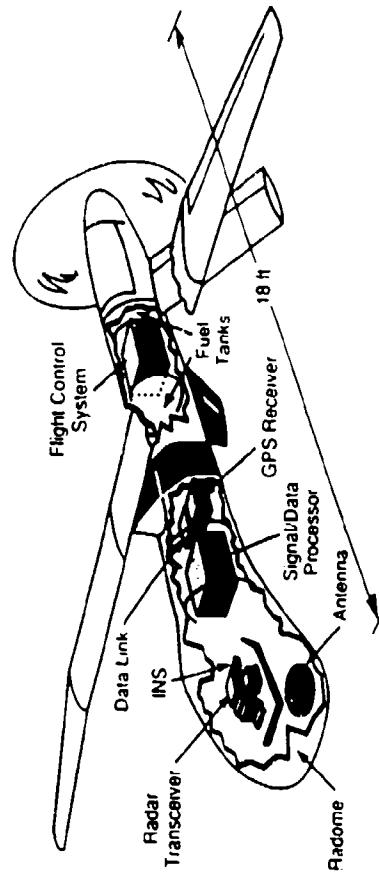

Figure 4.5. Configuration of Radar Payload in AMBER UAV

[1] C. E. Schwartz, T. G. Bryant, J. H. Cosgrove, G. B. Morse, and J. K. Noonan, "A Radar for Unmanned Air Vehicles," The Lincoln Laboratory Journal, Vol. 3, No. 1 (1990).

TECHNICAL ISSUES

The main objective of the FLARE concept is to provide surveillance and tracking of high-value mobile targets from a point in time when the target's position is known until the time when the attacker arrives. By doing so, the attacker's mission can be accomplished more efficiently and safely because the search time can be kept reasonably limited. While the concept appears at first blush to be plausible, several technical issues must be addressed:

1) **Target Mobility** --

   How mobile are the missile launchers of interest? How fast can they tear down after launch? How fast can they travel? How is their travel confined? Can they move across soft sand, for instance?

2) **Time-On-Station Requirements** --

   What is the on-station time or "hang-time" required of the FLARE radar? This time determines the allowable platform options and/or maximum weight of the radar payload. The hang-time depends on how long the attacker takes to arrive in the vicinity of the target cue.

3) **Coverage Requirements** --

   What is the required detection range of the radar sensor? Given the target's mobility, the hang-time determines how far the target can move before the attacker arrives, and thus sets the maximum detection range capability of the radar. The required detection range is also affected by sensor drift, due to winds for example, as well as a requirement to stand-off to avoid the so-called Nadir hole in the radar coverage. To a lesser extent, the maximum range also depends on the target cue accuracy.

The detection range of the system is the primary driver to the radar system's size in terms of the necessary power, antenna aperture, and required signal processing which in turn drives overall payload size and weight.

There is an interesting trade-off to be made between a smarter, smaller, maneuverable sensor versus a bigger, "dumb", non-maneuverable sensor. The non-maneuverable FLARE must have a relatively long range capability to track possible targets as they move away from the launch point. The smart sensor would be a radar that had a target discrimination capability as well as some surveillance capability. The maximum range required of the smart sensor could be very short with a resulting decrease in required power and aperture, and therefore size and weight. With a smaller, smarter sensor, more of the FLARE's size and weight could then be devoted to making the vehicle maneuverable and therefore able to follow the target.

4) **Booster Operations** --

Given the required hang-time and radar detection range, the type of FLARE platform and its size and weight can be estimated. This in turn dictates the size and type of launch vehicle required to very quickly deliver the FLARE to the vicinity of the target cue. Pershing or Lance missiles are desirable candidates because they are road mobile themselves, they have significant range/payload capability, and the boosters may soon be surplus items after their nuclear warheads are removed as a result of the INF Treaty.

5) **Launch and Deployment Loads** --

Deployment of the FLARE from a ballistic missile carries with it a number of technical difficulties. The FLARE must be able to withstand aerodynamic forces associated with deployment at speeds up to Mach 8, and be able to slow

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down to a velocity ideally below 100 kts (related to clutter notch, discussed below) at an altitude consistent with the hang-time requirements.

6) **Target Detection In Clutter --**

The ideal FLARE platform is one which is stationary in space so that the clutter Doppler extent is minimized. In this case, the radar is blind only to stationary targets or targets moving perpendicular to the radar's line-of-sight since these targets are obscured by the large ground clutter return at the same Doppler frequency. For a moving radar, there is a wider range of target velocity vectors which are obscured by clutter at different Doppler within the main beam of the radar. This range of non-detectable target velocities is wider when the radar beam is pointed perpendicular to its own velocity vector because the Doppler spread across the beam is wider in that direction. For a radar moving straight down, this implies the clutter Doppler width is worse near the horizon independent of the azimuth look direction. One of the issues to be examined is the effect of clutter broadening on target detectability for the various platform options. In any event, it may be necessary to deploy two FLAREs to ensure target detectability.

7) **Cost --**

Perhaps the most important issue is whether or not such a concept could be made cost-effective. Could an existing radar be used in this role? Could existing, cheap tactical ballistic missiles (such as left over from the INF Treaty) be used to launch the payload? Does the payload need to be recoverable to be cost-effective? What alternative concepts might be more cost-effective?

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APPENDIX A
ON THE USE OF THE GRADIENT TO
DETERMINE BISTATIC SAR RESOLUTION

G.P. Cardillo

INTRODUCTION

In evaluating the performance of a Bistatic SAR System it is important to determine the regions on the ground which satisfy range and cross-range resolution requirements. The vector gradient may be used to derive these resolutions, producing equations which in addition to providing insight into the problem may easily be implemented in computer code.

Figure A.1 shows the parameters of the problem. $\bar{P}_1$ and $\bar{P}_2$ are the vectors to the locations of the receiver and transmitter respectively, $\bar{V}_1$ and $\bar{V}_2$ are their velocities, and $\bar{r}$ is a point in the ground plane at which the resolution is to
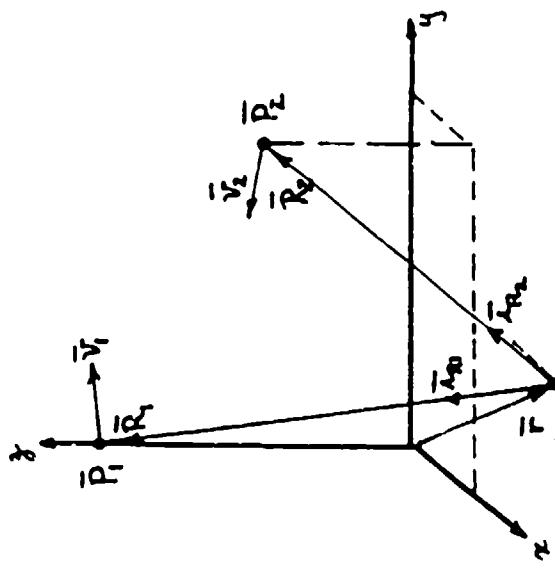
Figure A.1. Bistatic SAR Geometry

be determined. The radar will be assumed capable of measuring differences in time of arrival and frequency. The resolution in range in the vicinity of $\bar{r}$ will be shown to be directly related to the time resolution while the resolution in cross range will be related to the frequency resolution and the direction of the range resolution.

The following sections discuss Bistatic range resolution; Bistatic Doppler resolution; the definition of cross-range resolution in terms of Doppler and range resolution; and results from a computer code implementing the equations derived.

RANGE RESOLUTION

Assume a transmitter located at $\bar{P}_2$ radiates a pulse which is reflected from a point, $\bar{r}$, and is received at point $\bar{P}_1$.

The total transit time is given by

$$t(\bar{r}) = \frac{1}{c} \left[|\bar{R}_1| + |\bar{R}_2| \right] \quad \text{(sec)} \qquad (1)$$

where $\bar{R}_1$ and $\bar{R}_2$ are the vectors from $\bar{r}$ to $\bar{P}_1$ and $\bar{P}_2$ respectively.

A surface of constant arrival time consists of the points satisfying $t(\bar{r}) = $ constant .

The gradient of t is defined as

$$\nabla t = \left[\frac{\partial t}{\partial x} \bar{i} + \frac{\partial t}{\partial y} \bar{j} + \frac{\partial t}{\partial z} \bar{k} \right] = -\frac{1}{c} \left[\bar{i}_{R1} + \bar{i}_{R2} \right] \quad \text{(sec/m)} \qquad (2)$$

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where $\bar{i}_{R1}$ and $\bar{i}_{R2}$ are unit vectors from $\bar{r}$ to $\bar{P}_1$ and $\bar{P}_2$ respectively.

The change in t (dt) for a change in $\bar{r}$ ($\overline{dr}$) is given by $dt = -\overline{dr} \cdot \overline{\nabla \tau}$. Since dt is maximum when $\overline{dr}$ is along $\overline{\nabla \tau}$, the gradient $\overline{\nabla \tau}$ represents the direction which maximizes the change in arrival time. Similarly the maximum dt for movement in the ground plane is along the projection of $\overline{\nabla \tau}$ into the ground plane $\overline{\nabla \tau}_G$. Since a receiver can measure differences in arrival time inversely proportional to the bandwidth B, the range resolution in the ground plane can be written

$$\bar{S}_t = \frac{\left(\frac{1}{B}\right)}{|\overline{\nabla \tau}_G|} \, \bar{i}_{\tau G} \quad (m)$$ (3)

where $\bar{i}_{\tau G}$ is unit vector in the direction $\overline{\nabla \tau}_G$. Thus using Eqs. (2) and (3) the range resolution at any point in the ground plane may be determined. Note from Eq. (2) that the gradient and hence the range resolution depends only on the directions to the transmitter and receiver and not the distances.

DOPPLER RESOLUTION

A similar procedure is used to obtain an expression for Doppler resolution. From Figure A.1 the Doppler shift of the signal received from a point $\bar{r}$ may be written

$$f(\bar{r}) = \frac{1}{\lambda} \left[\bar{v}_1 \cdot \bar{i}_{r1} + \bar{v}_2 \cdot \bar{i}_{r2} \right] \quad (Hz)$$ (4)

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The surface of constant Doppler shift satisfies $f(\bar{r}) = \text{const}$.

The gradient of f at the point $\bar{r}$ is

$$\bar{\nabla f} = \left[\frac{\partial f}{\partial x}\bar{i} + \frac{\partial f}{\partial y}\bar{j} + \frac{\partial f}{\partial z}\bar{k}\right]$$

$$= -\frac{1}{\lambda}\left\{\frac{1}{|\bar{R}_1|}\left[\bar{v}_1 - (\bar{v}_1 \cdot \bar{i}_{R1})\bar{i}_{R1}\right] + \frac{1}{|\bar{R}_2|}\left[\bar{v}_2 - (\bar{v}_2 \cdot \bar{i}_{R2})\bar{i}_{R2}\right]\right\} \quad (Hz/m)$$

(5)

For motion in the ground plane, the change in f is maximum along the projection of $\bar{\nabla f}$ in the ground plane, $\bar{\nabla f}_G$.

A receiver can measure differences in frequency inversely proportional to the processing time T.

The Doppler resolution at any point in the ground plane is

$$\bar{S}_f = \frac{\left(\frac{1}{T}\right)}{|\bar{\nabla f}_G|}\bar{i}_{fG} \quad (m)$$

(6)

where $\bar{i}_{fG}$ is the unit vector in the direction $\bar{\nabla f}_G$.

Using Eqs. (5) and (6), the Doppler resolution at any point in the ground plane may be determined. Note from Eq. (5) the Doppler resolution depends on the angular rate of the transmitter and receiver about the point $\bar{r}$. Thus, for example, for a high altitude transmitter and low altitude receiver, the receiver dominates the Doppler resolution.

CROSS-RANGE RESOLUTION

In SAR mapping the size of the image pixels are an important measure of the system performance. As shown in Figure A.2, the ground range and Doppler resolutions derived do not by themselves specify the pixel size in a meaningful way since they are not necessarily orthogonal. Defining θ to be the angle between the gradients, i.e., $\theta = \cos^{-1}(\bar{i}_{tG} \cdot \bar{i}_{rG})$, a representation of the cell size is its area given by

$$A = \frac{|\bar{S}_f| \, |\bar{S}_t|}{\sin \theta} \quad (m^2)$$

(7)

The cross-range resolution can be defined to produce an equivalent rectangle with the same pixel area

$$\Delta_{XR} = \frac{|\bar{S}_f|}{\sin \theta} \quad (m)$$

Using Eqs. (3), (6), and (7), the cross-range resolution at any point in the ground plane may be determined.

RESULTS

A computer program was written to implement Eqs. (1) to (7) at a grid of points in the ground plane and contours of constant resolution (in meters) were drawn. Figure A.3 shows the results for a 1000 km altitude circular orbit satellite transmitter and an aircraft receiver (⸱ ⸱ alt, 200 m/s). The radar bandwidth was 500 MHz and the integration time for all points in the plane was 10 sec. The ground region shown is 80 x 80 km centered on the aircraft which is travelling up the page. The satellite, which is moving to the right, is offset to the upper right so that its grazing angle at the center of the region is 45˚ .
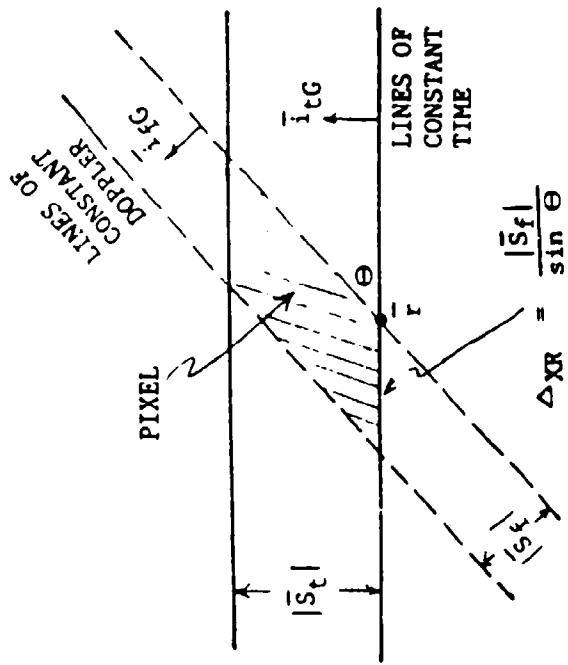
Figure A.2. Definition of Cross-Range Resolution, Δ_{XR}

Figure A.3a shows that the equivalent of the nadir hole for the monostatic SAR is located between the A/C and the satellite. Figure A.3b shows the twisting of the lines of constant Doppler due to the satellite and A.3c shows the cross-range resolution which results from the interaction of range and Doppler resolution. Figure A.3d shows the ground region for which the range and cross-range resolution are each less than 1 m.

Figures A.3 a,b,c. Contours of Constant Resolution in Meters

Figure 3d. Region of 1 m² Resolution

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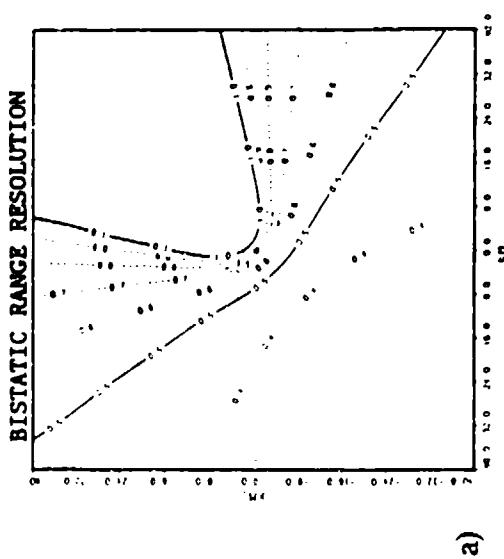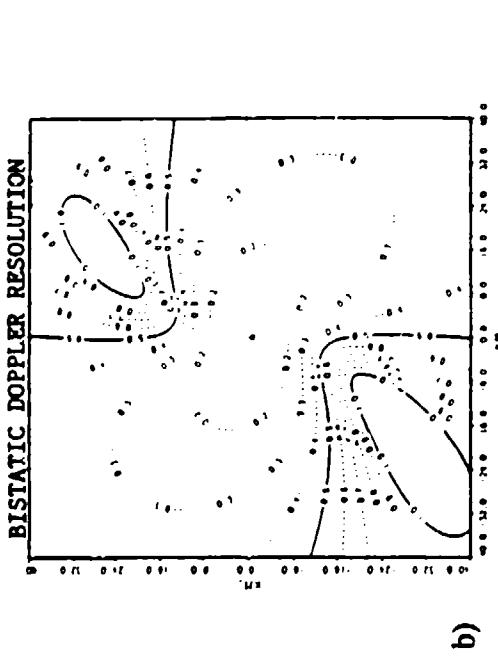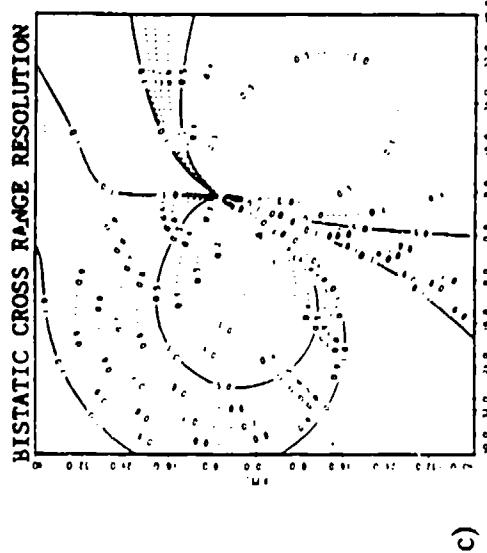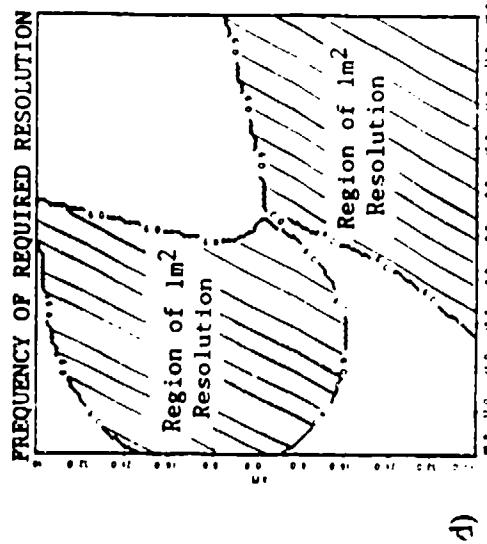
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APPENDIX B
MOTION COMPENSATION REQUIREMENTS

G.P. Cardillo

BISTATIC SAR
MOTION COMPENSATION REQUIREMENTS
RANGE MEASUREMENT [TO SOLVE TRIANGLE]

- FROM INS DATA

  - LIMITED ACCURACY

  - MIGHT RESOLVE RANGE AMBIGUITY

- FROM DIRECT RADAR MEASUREMENT

  - DIRECT PATH RECEIVER
    TO MEASURE (I+R-B)

  - WITH PRECISE CLOCKS IN XMITR AND RCVR
    RCVR KNOWS TIME OF XMIT

    -- THUS CAN DETERMINE (I+R)

    -- THUS CAN DETERMINE (B)

    -- FOR 3 M RANGE ACCURACY REQUIRES
       1E-12 CLOCK STABILITY

  - WAYS TO FIND (R AND I)

    -- USE RCVR MONOPULSE ANGLE (VARIABLE ACCURACY)

    -- XMITR MEASURE (I) AND DATA LINK TO RCVR

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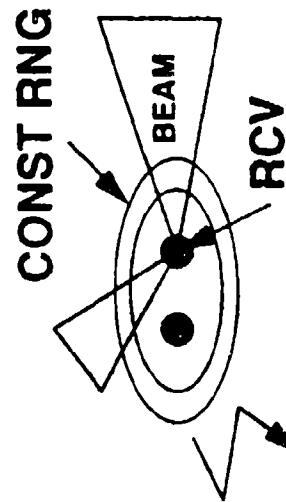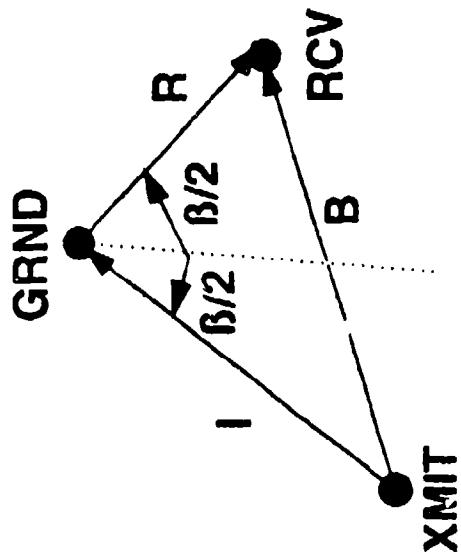
BISTATIC SAR
MOTION COMPENSATION REQUIREMENTS
DOPPLER MEASUREMENT [COHERENCY]
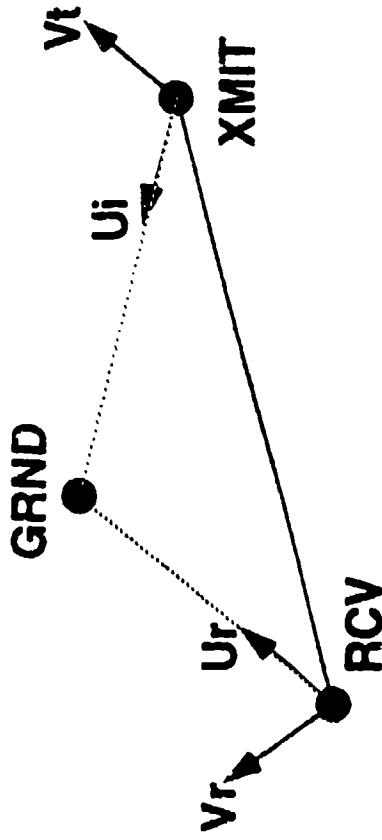
- PHASE LOCK RCV LO TO DIRECT PATH RETURN

  THEN FOR 4 DEG OVER PATH (I+R-B)

  LO STABILITY = 1E-9

- STABLE FREE RUN LO'S (NO DIRECT PATH REQD)

  THEN FOR 90 DEG QUAD PHASE OVER 10s INTEGRATION TIME
  LO STABILITY = 1E-11

- PHASE CORRECTION REQUIRED

  $\phi(t) = (2\pi / \lambda) \int \int (V_i \cdot U_i + V_r \cdot U_r - B) \, dt$: i.e., $\int$ (LOS RATES)

  where B is reqd only if direct path return is used to phase lock LO

MOTION COMPENSATION CONFIGURATION FOR BISTATIC SAR
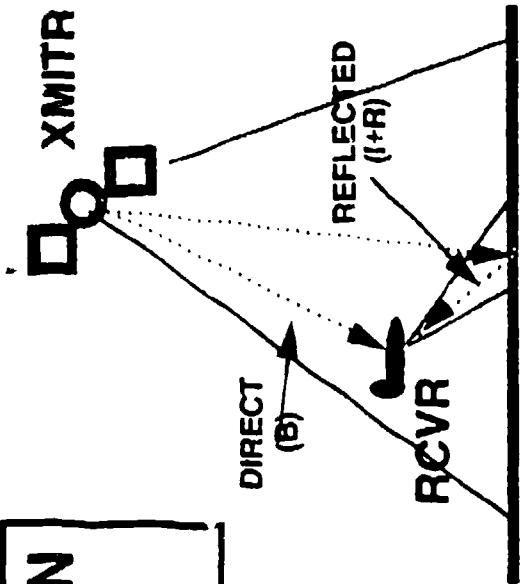
- RANGE CORRECTION

  PRECISION CLOCKS IN RCVR AND XMITR
  -- XMIT TIME KNOWN

  RCVR MEASURES DIRECT PATH (B)

  RCVR MEASURES REFLECTED PATH (I + R)

  RCVR USES MONOPULSE ANGLE TO OBTAIN (R)

- DOPPLER CORRECTION

  $\varnothing(t) = (2\pi / \lambda) \int (V_i \cdot U_i + V_r \cdot U_r) \, dt$

  V_r MEASURED AT RCVR

  V_t DETERMINED FROM SATELLITE EPHEMERIS

  NOTE : NO DATA LINK BTWN XMITR AND RCVR

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APPENDIX C
IONOSPHERIC FADING

G.P. Cardillo

SUMMARY
IONOSPHERIC FADING ERRORS

- BOTH AMPLITUDE AND PHASE FLUCTUATIONS RESULT FROM ELECTRON DENSITY IRREGULARITIES IN IONOSPHERE

  - MORE SEVERE AT LOW FREQUENCIES (VHF, UHF)

  - MORE SEVERE AT HIGH LATITUDES (> 60 DEG)

- SRT BISTATIC SAR FREQUENCY (X-BAND) AND THE OPERATIING LATITUDES (45-60 DEG) GREATLY REDUCES EFFECT

- ALCOR (5.6 GHZ) NEAR EQUATOR (8 DEG LAT) ROUTINLY IMAGES SATELLITES

- EVEN IF IT WERE A PROBLEM TO MONOSTATIC SATELLITE SAR BISTATIC SAR DIRECT PATH RADIATION WOULD ALLOW PULSE-PULSE CORRECTION OF PHASE VARIATIONS

IONOSPHERE ALTITUDE REGION
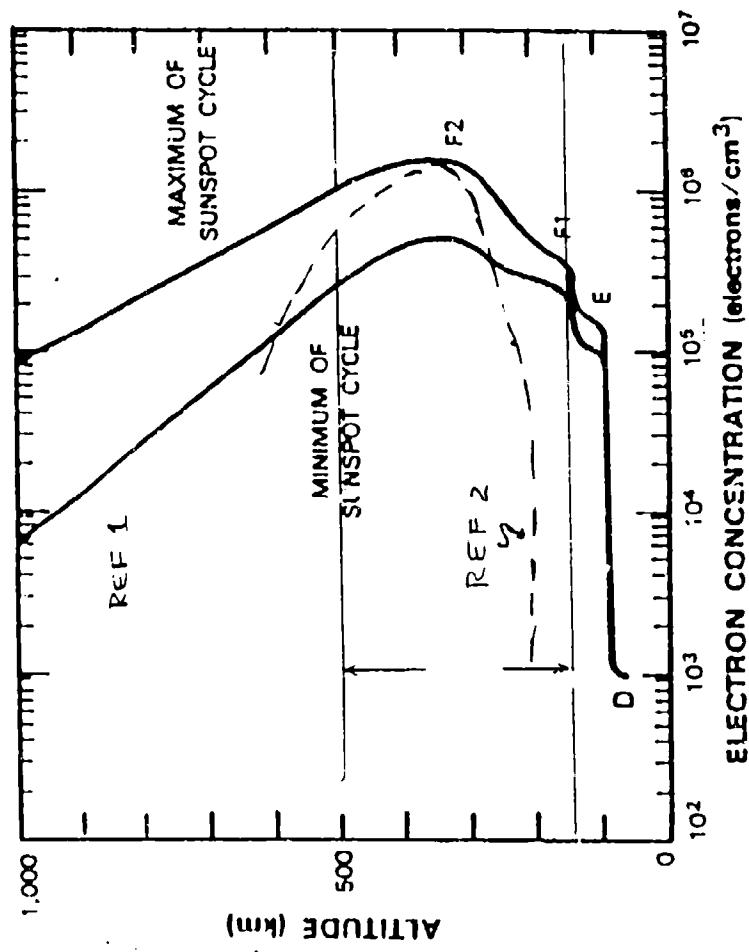
SCINTILLATION DUE TO THE IONOSPHERE

XMIT

Acoswt

IONOSPHERE

$A(t)\cos[wt+\emptyset(t)]$

ONE-WAY PATH

RCS
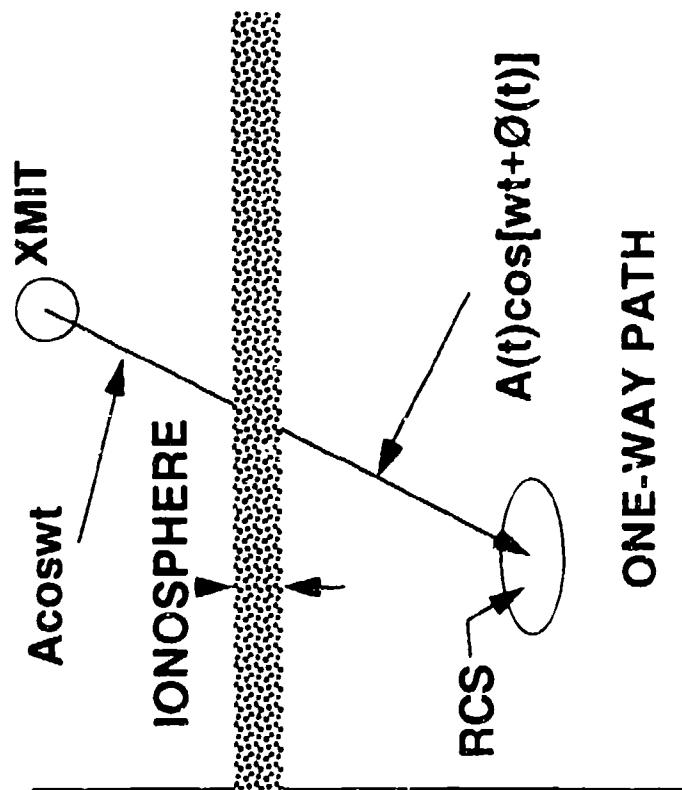
IST ORDER STATISTICS

A(t) = AMPLITUDE ~ RAYLEIGH

$\emptyset$t) = PHASE ~ UNIFORM

RCS ~ SWERLING 1

2ND ORDER STATISTICS (CORRELATION)

ρ = AUTOCORRELATION = $\exp[(-2\tau/\tau_0)]$

τ_0 = DECORRELATION TIME

TARGET $\tau_0 \rightarrow \infty$, (SWERLING 1)

IONOSPHERE $\tau_0 \gg T$, SLOW FADING $\Rightarrow$ S/N INTEGRATION GAIN = n

$\tau_0 \ll T$, RAPID FADING $\Rightarrow$ S/N INTEGRATION GAIN = 1

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IONOSPHERIC SCINTILLATION CAN BE A PROBLEM

WORST CASE

TWO-WAY PATH
SWERLING 1 TARGET
Pfa = 1 E-6
400 PULSES /DWELL

NOTE THE EFFECT ON THE
BISTATIC SYSTEM WOULD
BE LESS SINCE ONLY A
ONE-WAY PATH APPLIES

MEAN INTEGRATED S/N (dB / dwell)
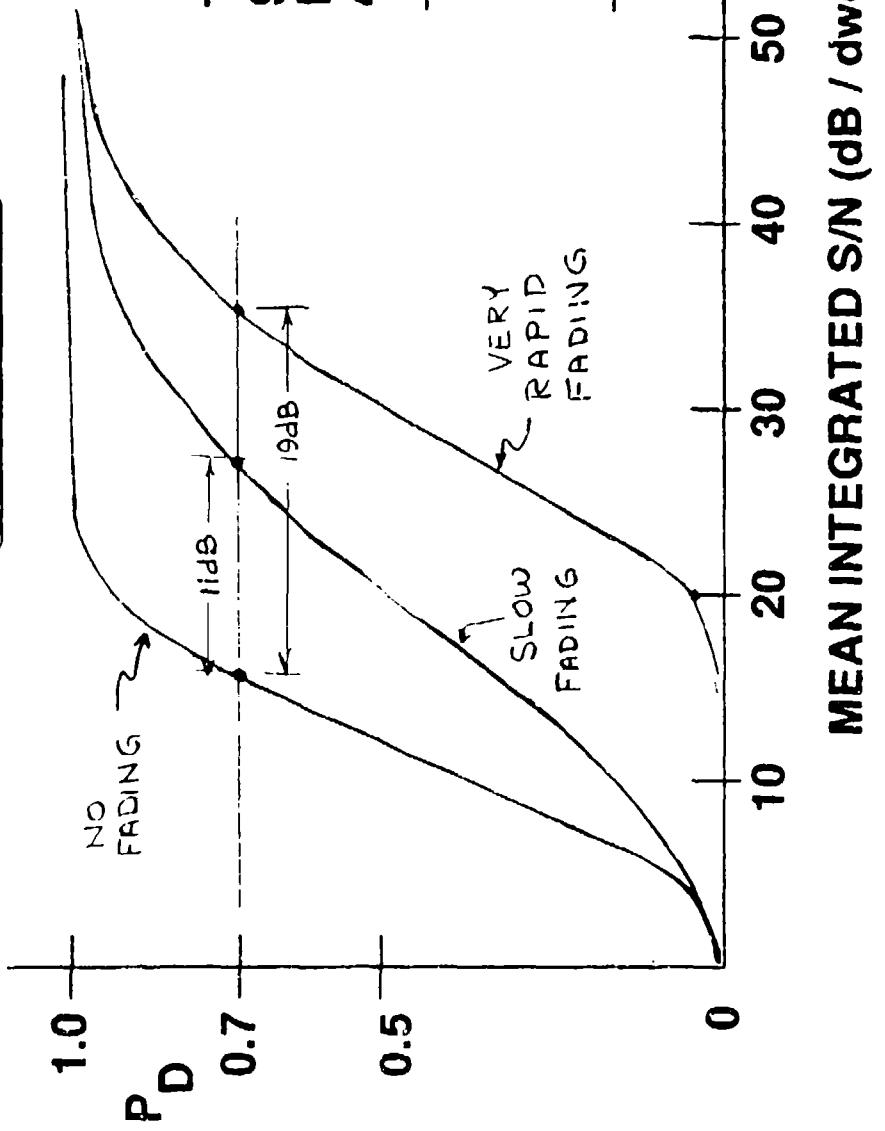
Dana and Knapp
(REF 3)

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BUT MITIGATING FACTORS ARE

1. LATITUDE REGION OF INTEREST

- FADING IMPORTANT : ± 20 DEG. LATITUDE AT NIGHT
  > 60 DEG. LATITUDE ALWAYS

DAY

NIGHT

UHF

BACKGROUND NOISE LEVEL

14 AUGUST, 1976 – DAYTIME
VHF

CALIBRATION PULSE

BACKGROUND NOISE LEVEL

11 AUGUST, 1976 – T_0 = 10:18 GMT
VHF

TIME (s) →

RCS (dBsm)
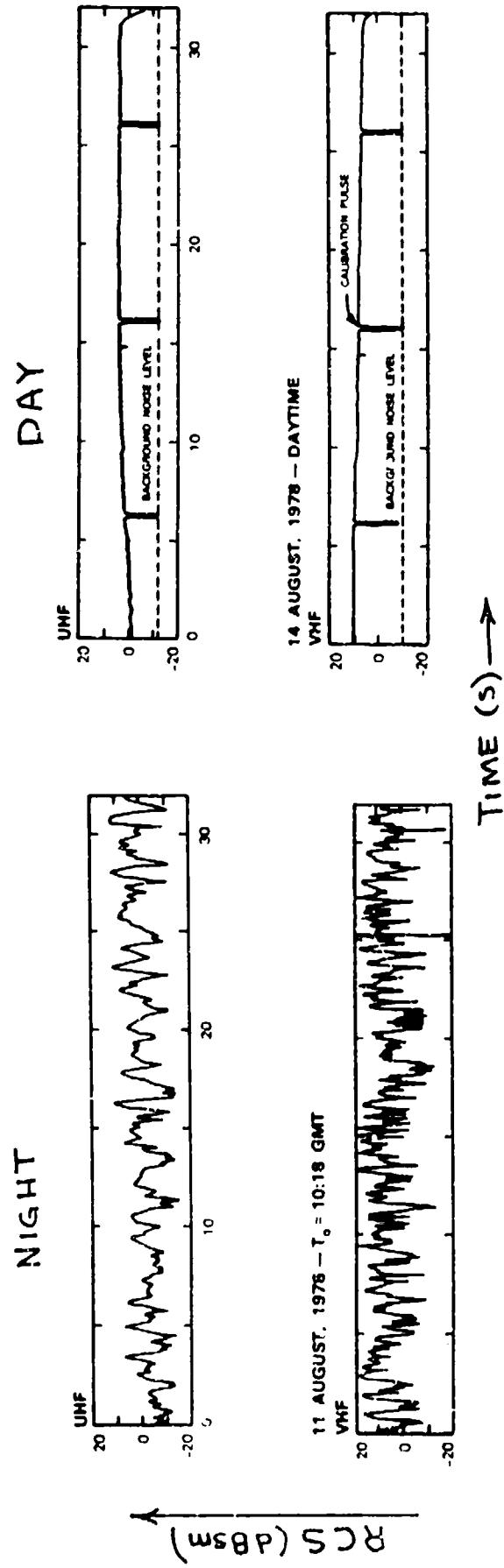
- FOR SRT PROBLEM : 45 - 60 DEG. LATITUDE

MITIGATING FACTORS : 2

2. FADING MORE PRONOUNCED AT LOWER FREQUENCIES

100
10
1

MAX
INTEGRATION
TIME (SEC)

.3   1   3   10   F, Ghz

1/F

ref 1

L-BAND

UHF

VHF
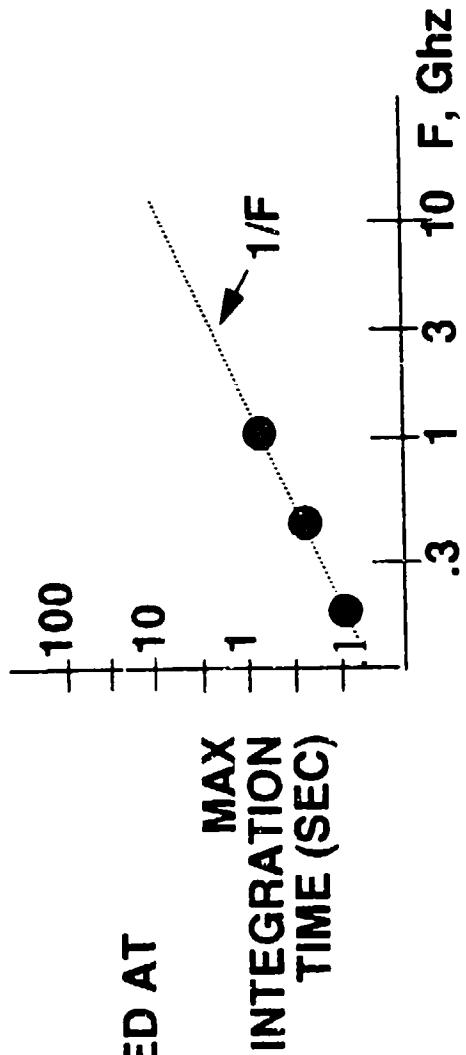
STABILIZED CYLINDRICAL SATELLITE
JOINT TRADEX/ALTAIR TRACK
CONDITIONS   10:00 p.m. LOCAL TIME
NEAR PEAK OF SUNSPOT CYCLE
900 km ALTITUDE

1320 MHz
415 MHz
166 MHz

RADAR CROSS SECTION (dBsm)
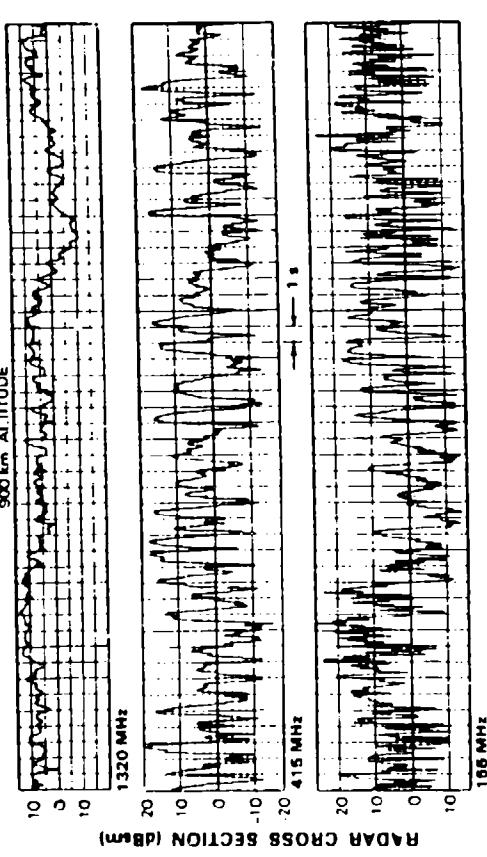
MITIGATING FACTORS : 3, 4

3. ALCOR ROUTINELY IMAGES SATELLITES AT 5.6 Ghz NEAR EQUATOR
RINO AND OWEN (REF 4)

4. BISTATIC OPERATION WITH RECEIVER BELOW IONOSPHERE
DIRECT PATH RADIATION ALLOWS CORRECTIONS TO BE APPLIED
- ON A PULSE-PULSE BASIS
- FOR EITHER RAPID OR SLOW FADING
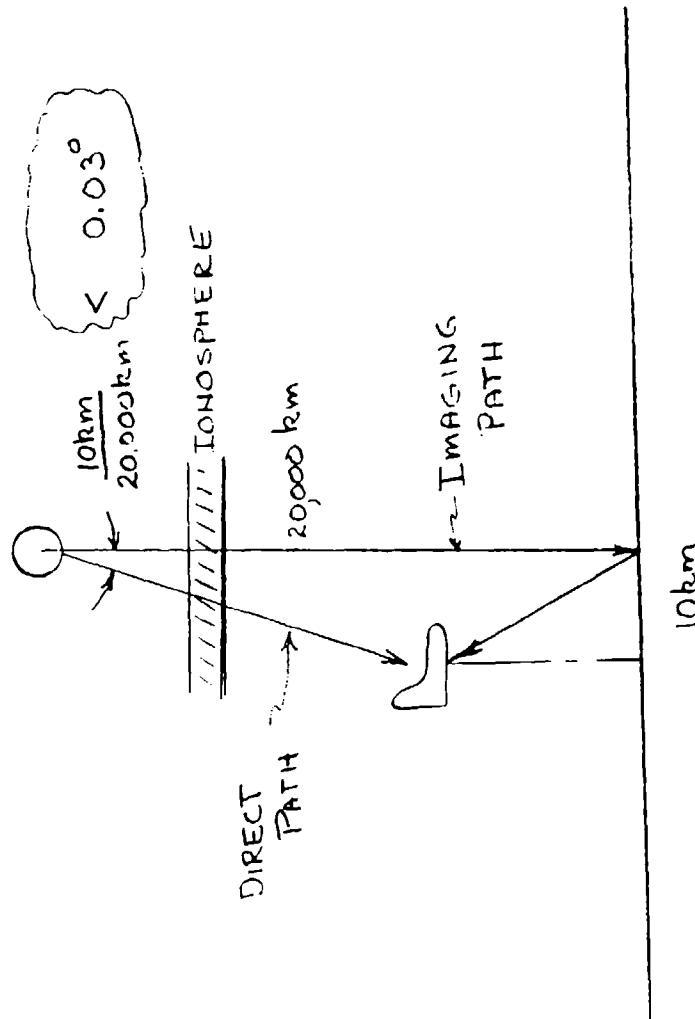
CORRECTION OF IONOSPHERIC PHASE ERROR

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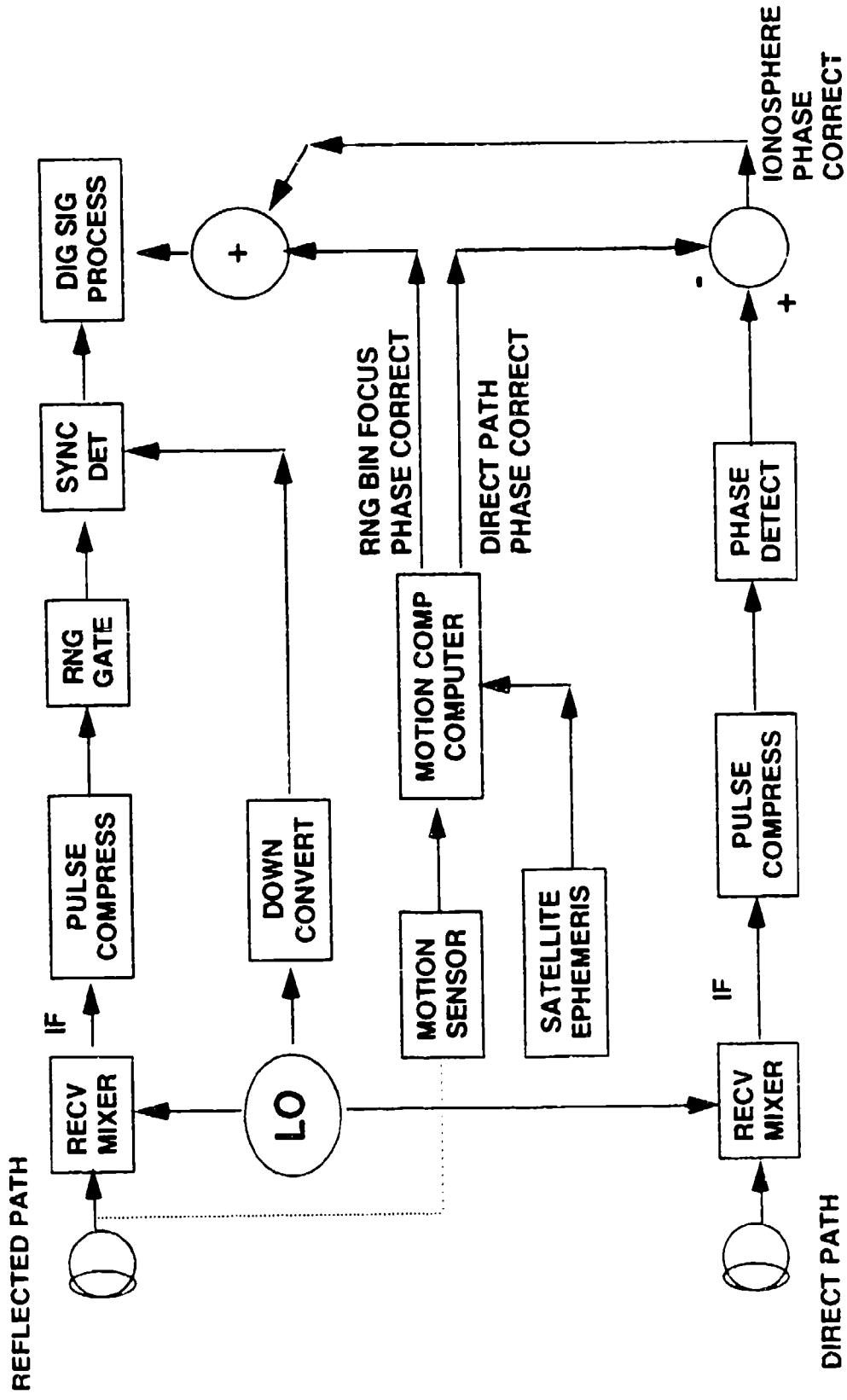
REFERENCES

1. Tsandoulas G.N., "Space Based Radar, Frequency and Altitude Tradeoffs " Project Report SRT-23, MIT Lincoln Laboratory, Oct 86   (Unclassified)

2. Szuszczewicz E.P. and Rodriguez P., Singh M., Mango S."Ionospheric Irregularities and Their Potential Impact on Synthetis Aperture Radars ' ,Radio Science, Vol 18 Nu 5, Oct 83 (Unclassified)

3. Dana R.A., Knepp D.L., " The Impact of Strong Scintillation on Spaced Based Radar Design: 1:Coherent Detection " IEEE Trans on Aerospace and Electronic Systems, No. 19, Jul 83 (Unclassified)

4. Rino, C.L., Owen, J. " Propagation Effects in SAR and Isar Coherent Radar Imaging" SRI International, DNA-TR-88-30, Jan 88 (Unclassified)

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APPENDIX D
DETECTION AND DISCRIMINATION ANALYSIS

G.P. Cardillo

DETECTION AND DISCRIMINATION OF "LPI" SAR

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AIRCRAFT
MONOSTATIC SAR

SIDELOBE

MAINBEAM

GROUND RECIEVER

OTHER RADIATION
SOURCES

AWACS
2

AIR BORNE
INTERCEPTOR
2

SAM
2
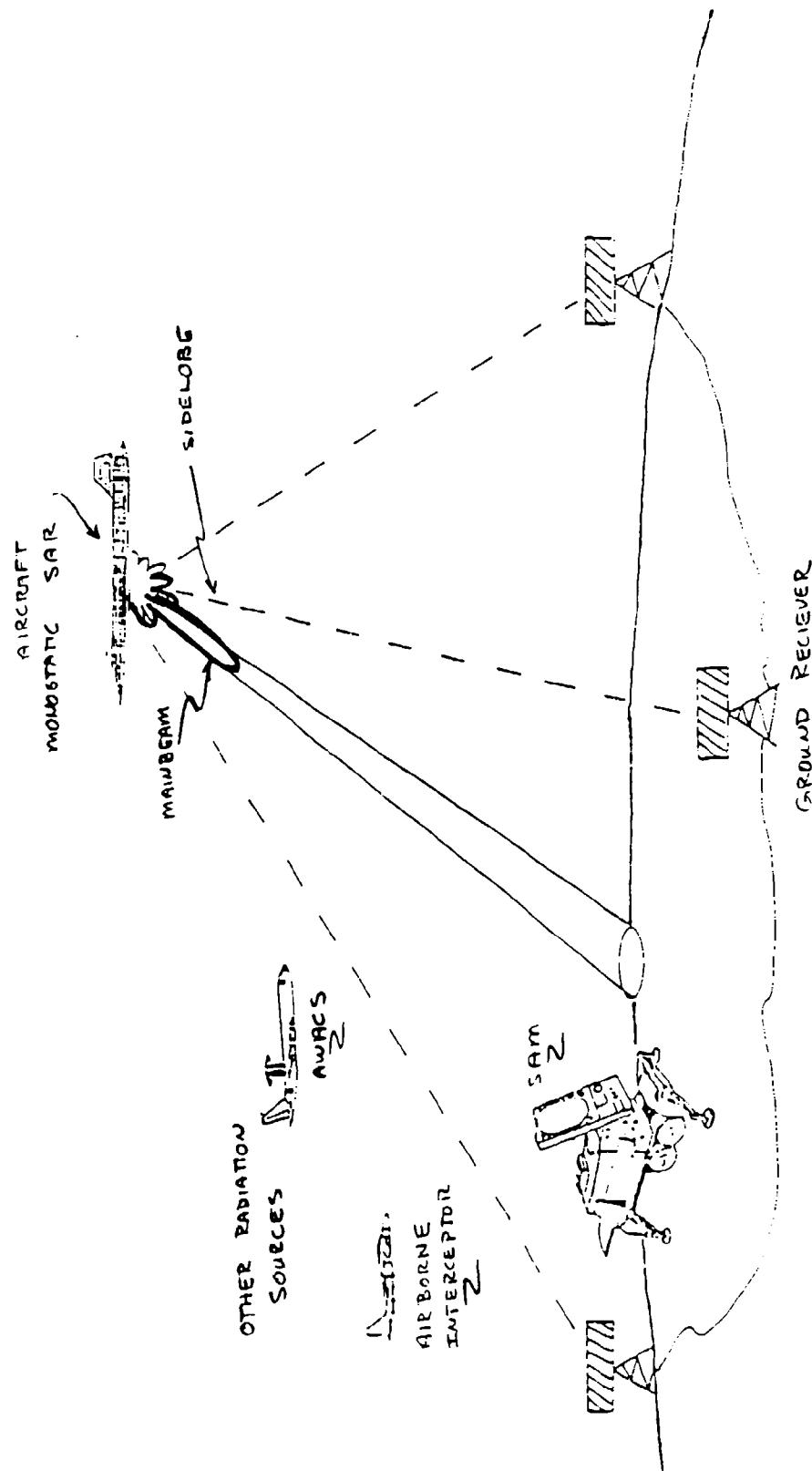
GROUND STATION FOR A/C SAR RADIATION DETECTION

JAMMING RECEIVER

4 FOOT x 1 FOOT
PARABOLIC CYLINDER
ANTENNA
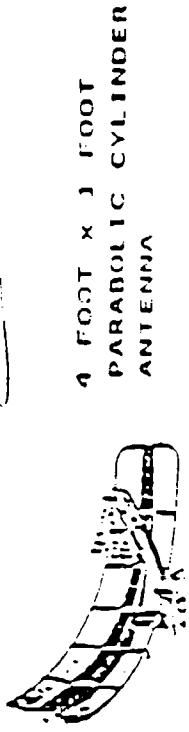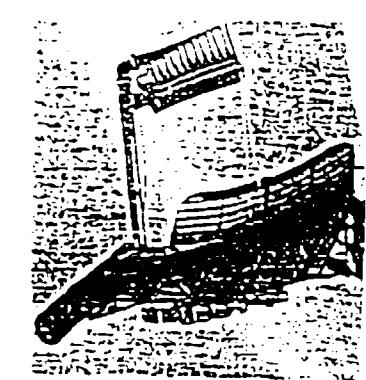
- TYPICAL RADAR RECEIVER
  - NOT SUPER COOLED
  - STANDARD SIGNAL PROCESSING

- ANTENNA BEAM 2° x 10°
- 4 beams Stacked in elevation
- ANTENNA GAIN = 35 dB

- SCAN RATE 360° IN 6 SECONDS

SAMPLE OF STACKED BEAM FEED

POSTULATED SAR RECEIVER PARAMETERS

SWEPT BANDWIDTH	1 GHZ / 16 mS
FILTER BANDWIDTH	150 MHZ (20 MHZ FOR DISCRIM.)
ANTENNA BEAMWIDTH	2 DEG. X 10 DEG SEARCH
ELEVATION COVERAGE	40 DEG. 4 STACKED 10 DEG BEAMS
ANTENNA SIZE	4 X 1 FEET
ANTENNA GAIN	35 dB
ANT SCAN RATE	360 DEG / 5.0 SEC
NOISE FIGURE (PRE-AMP)	3 dB
RECEIVER LOSS	6 dB

Range To Jammer For Specified S/N

$$R_J^2 = R_S^4 \left[\frac{4\pi}{G_{ES}} \left(\frac{G_{IJ}}{G_{IS}}\right)\left(\frac{G_{CJ}}{G_{CS}}\right)\left(\frac{G_{SL}}{\sigma}\right)\left(\frac{L_S}{L_J}\right) \right] \frac{P_S}{P_J}$$

- ML Antenna Gain
- Integration Gain
- Pulse Compression Gains
- SAR SL Gain, Target RCS
- Losses
- Desired Rcv Power After Processing

where S - SAR
       J - Jammer
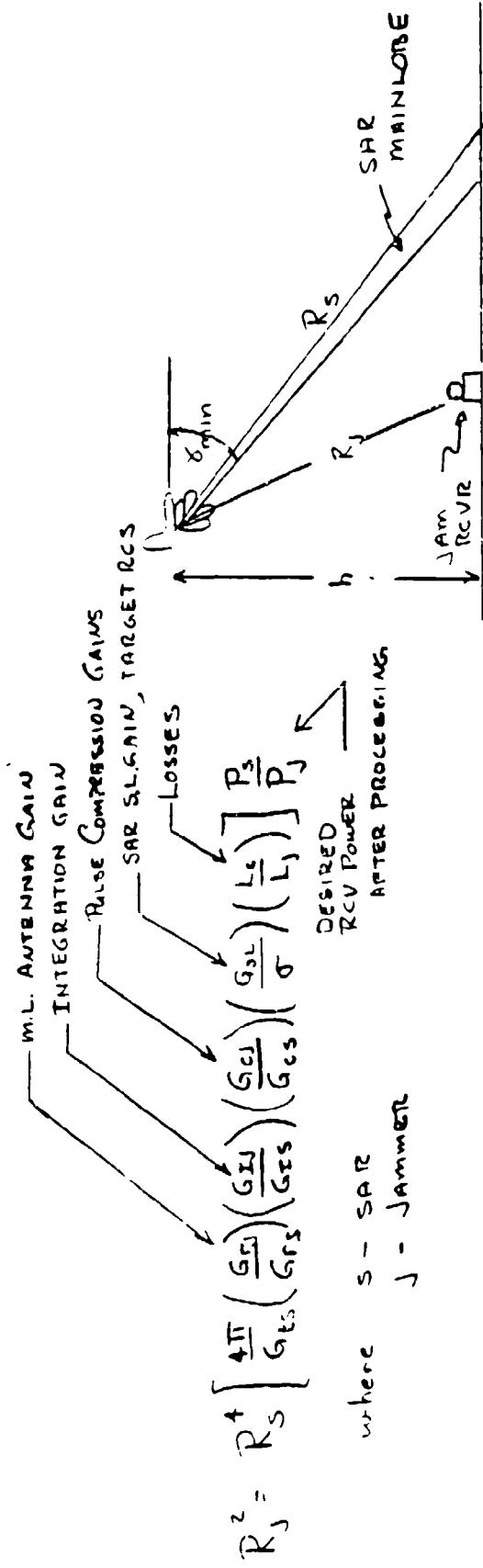
Key Points

- Jam Rcvr in SAR Sidelobes

- LPI SAR Power Managed vs δ

- Pulse-Pulse Integration Gain
  SAR = 5000
  J Rcv = 1

- Pulse Compression Gain
  SAR = 5000
  J Rcv = (25ω)·7

- Range
  SAR - Two way Range (R_S^4)
  J Rcv - one way Range (R_J^2)

- Antenna Gain
  SAR - two-way mainlobe gain
  J Rcv - one way mainlobe gain

- Rcv Noise
  SAR = J Rcv
  SAR = J Rcv $P_S = P_J$

- Desired S/N
  SAR = J Rcv

- $\lambda = .03$ cm $h = 10$ km
  Bw = 500 MHz $R_S = \dfrac{10E3}{\sin \delta_{min}}$

- $\boxed{R_J = \dfrac{19.5E3 \left(\dfrac{G_{SL}}{\sigma}\right)^{1/2}}{\sin^2 \delta_{min}}}$

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M.L. ANTENNA GAIN

INTEGRATION GAIN

PULSE COMPRESSION GAIN

SAR SL GAIN, TARGET RCS

LOSSES

$$R_j^2 = R_s^4 \left[\frac{4\pi}{G_{ts}} \left(\frac{G_{tj}}{G_{rs}}\right)\left(\frac{G_{cj}}{G_{cs}}\right)\left(\frac{G_{ij}}{\sigma}\right)\left(\frac{L_s}{L_j}\right) \right] \frac{P_s}{P_j}$$

DESIRED RCV POWER AFTER PROCESSING

SAR XMIT ANTENNA GAIN

where S - SAR
       J - JAMMER

SAR MAINLOBE

R_s

σ_{min}

R_j

h

JAM RCVR

Assume

1. JAM RCV NOISE = SAR RCV NOISE

2. SAME S/N REQD FOR DETECTION (JAMMER & SAR) $\Rightarrow P_s = P_j$

3. $G_{rj} = G_{rs} = 35\,dB$: MAINLOBE GAINS ARE EQUAL

4. $L_s = L_j$: RCV LOSSES ARE EQUAL

5. $h = 10\,km \Rightarrow R_s = \dfrac{10^4}{\sin\gamma_m}$; where, γ_m = MIN SAR GRAZING ANGLE

6. SAR PRF = 5000 $\Big\} \Rightarrow i_s = 5000$

7. SAR INTEGRATION TIME = 1 sec

8. $G_{ij} = 1$: PULSE INTEGRATION GAIN

9. JAM RCV NON-COHO INTEGRATES i pulse compres $\Rightarrow G_{cj} = (2500)'$: JAM RCV INTEGRATION GAIN BY THE JAMMER   [SEE NEXT VIEWGRAPH]

$$R_j^2 = \left(\frac{1E^4}{\sin\gamma}\right)\left[\left(\frac{4\pi}{10^{3.5}}\right)(1)\left(\frac{1}{i_s}\right)\left(\frac{2500^7}{5000}\right)\left(\frac{G_{sr}}{\sigma}\right)(1)\right](1)$$

Jammer Pulse Compression Gain

Assume SAR Pulse length = $10\mu s$

       BW   = 500MHz $\Rightarrow$ .002 μs

Then 5000 Bit Pulse Code Used


←——— 5000 bits ———→

Jammer Receiver employes 500 MHz BW

Detects every 0.002 μsec

Non Coho integrates over 10μs intervals

At worst it would integrate across 2500 bits
in integration window

2500 bits

SAR Pulse 5000 bits

Jammer Non-Coho Integration windows
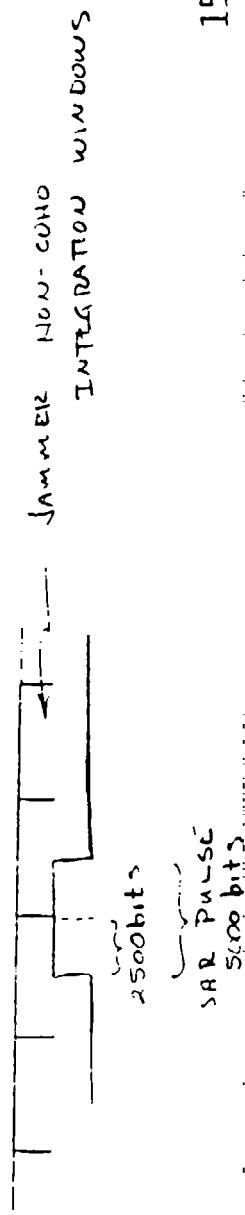
Jammer Maximum Detection Range
vs
SAR Minimum Grazing Angle

$$R_J = \frac{19.5E3}{\sin \gamma} \left(\frac{G_{SL}}{\sigma}\right)^{\frac{1}{2}}$$

$G_{SL} =$ SAR Ant SL level (dBA)

$\sigma =$ Target RCS (dBsm) For SAR Detection

# of Jammers/MOB

$\left(\frac{400}{R_J}\right)^2$

$\frac{400}{R_J}$

1
2
3
4
10
16
64
400

$\frac{G_{SL}}{\sigma}$

10

eg $G_{SL} = -10$ dBm $\sigma = -10$ dBsm

100 SITES

40 km

SAR MIN GRAZING ANGLE, γ

15   30   45   60

SAR Min Grazing Angle, γ

R_J

400

Jammer Max Detect Rng (km)

300

200

100
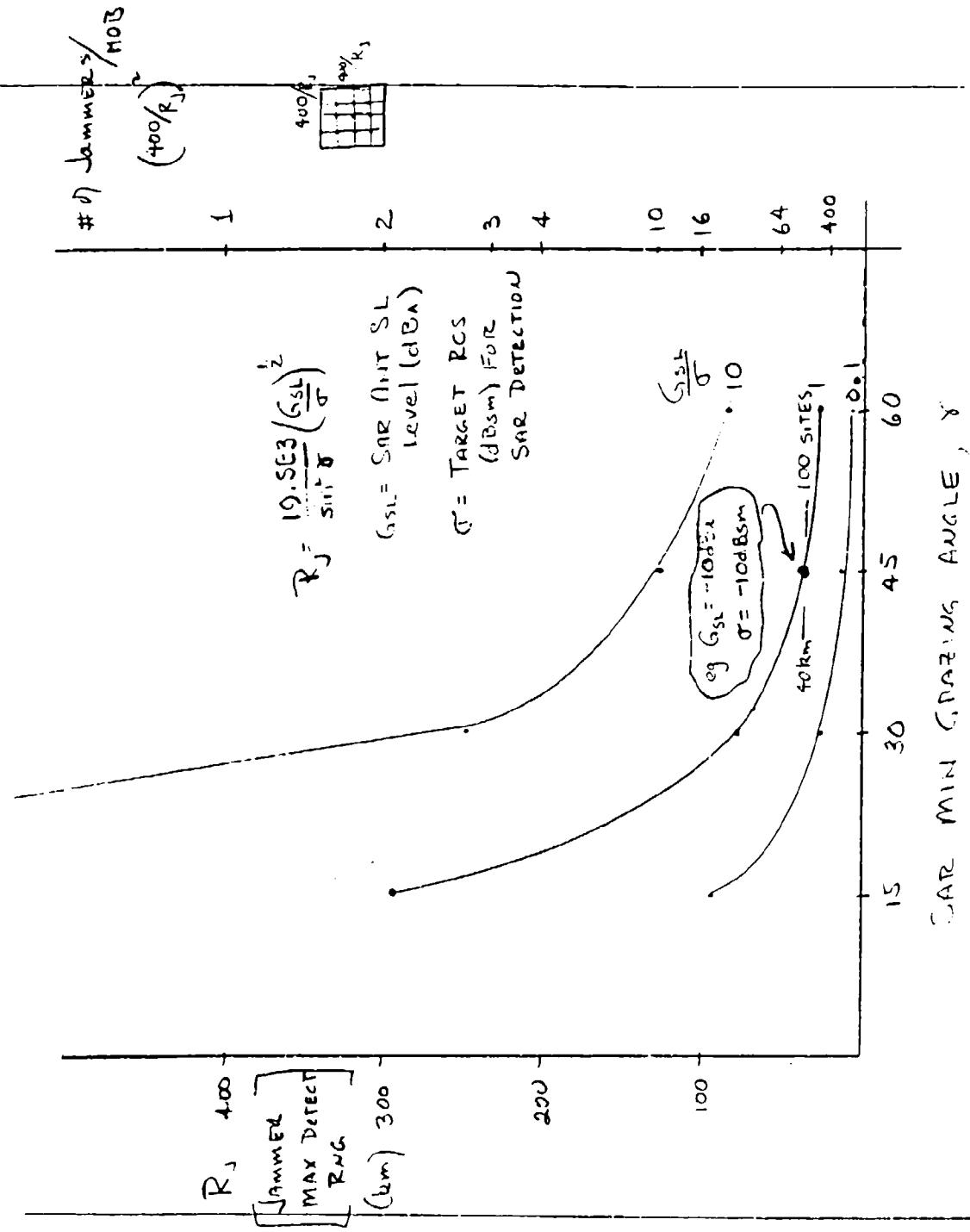
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# APPENDIX D
JAMMING HYBRID BISTATIC SAR

-SUMMARY-
JAMMING HYBRID BISTATIC SAR

BROADBAND NOISE JAMMING

- SATELLITE TRANSMITION -- EASILY DETECTED

  - JAMMER RECEIVER IN XMIT MAINBEAM

  - USING SIMPLE OMNI RCV ANTENNA ≈10 DB SINGLE PULSE S/N

- A/C RECEIVER HARD TO JAM - BECAUSE IT CANNOT BE FOUND

  - JAMMER BEAM CANOT BE DIRECTED

  - JAMMER TRANSMITTER IN SAR REC SL

  - LARGE BANDWIDTH REQUIRED (500 MHZ)
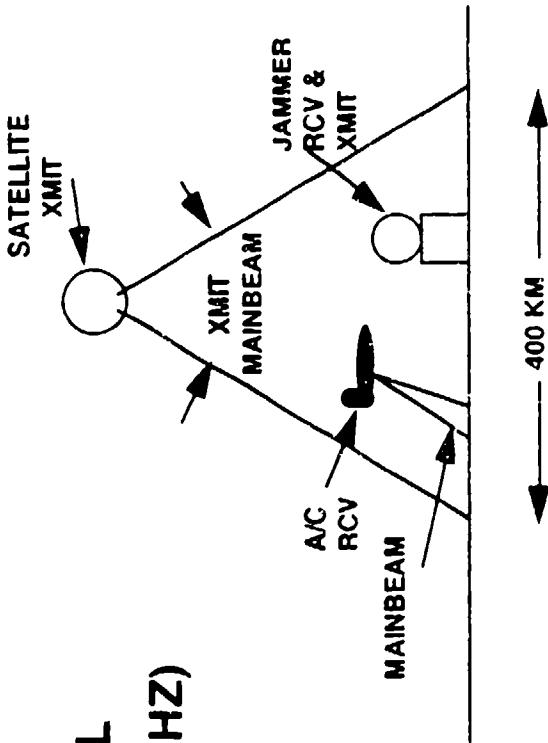
62 KW < JAMMER POWER REQD < 6MW
(PER JAMMER)

SATELLITE
XMIT

JAMMER
RCV &
XMIT

XMIT
MAINBEAM

A/C
RCV

MAINBEAM

400 KM

POWER IS INDEPENDENT OF SATELLITE ALTITUDE
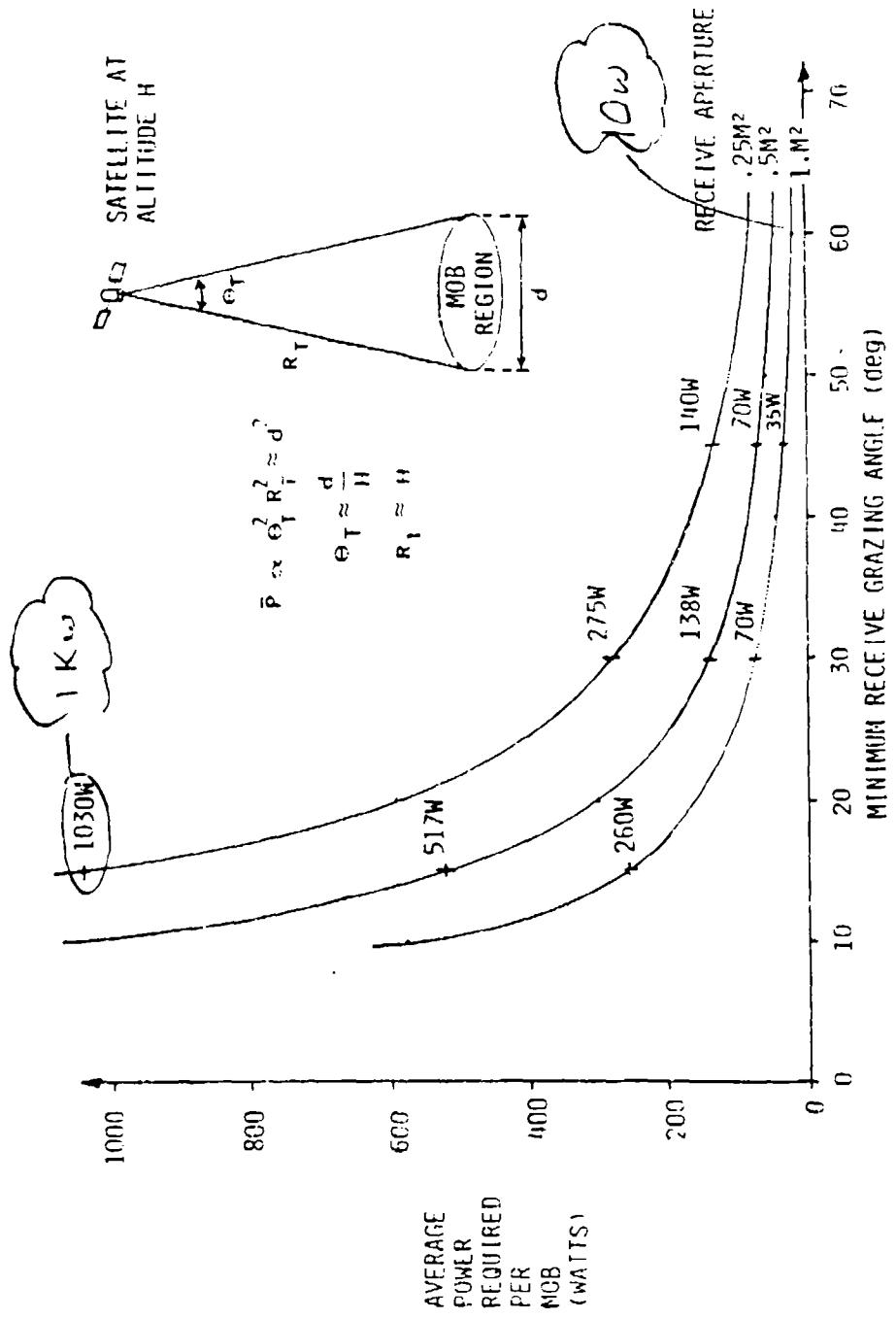
BISTATIC SAR SATELLITE TRANSMISSIONS ARE EASILY DETECTED

SATELLITE XMIT

XMIT MAINBEAM

JAMMER RCV & XMIT

A/C RCV

MAINBEAM

D

PEAK PWR DENSITY OVER REGION D^2

$$P_K = \frac{P_a J}{D^2} \ (w/m^2) \quad \text{where } P_a = \text{Transmit Avg Power}$$

SINGLE PULSE: S/N at JAMMER w/ OMNI ANTENNA $A = \frac{G \lambda^2}{4\pi} = \frac{\lambda^2}{4\pi}$

$$\frac{S}{N} = \frac{P_G T A}{(kTFL)d^2} = \frac{P_G T \lambda^2}{4\pi (kTFL)d}$$

From BISTAT AVG PWR RAD

$$10w < P_a < 1kw$$

↳ use for lowest S/N at JAMMER

SINGLE PULSE: $\frac{S}{N} = 7.5 dB$

Note
- Since satellite position is known directive Jammer Rcv antenna gain can be used
- Jammer Rcv antenna given and integration gain
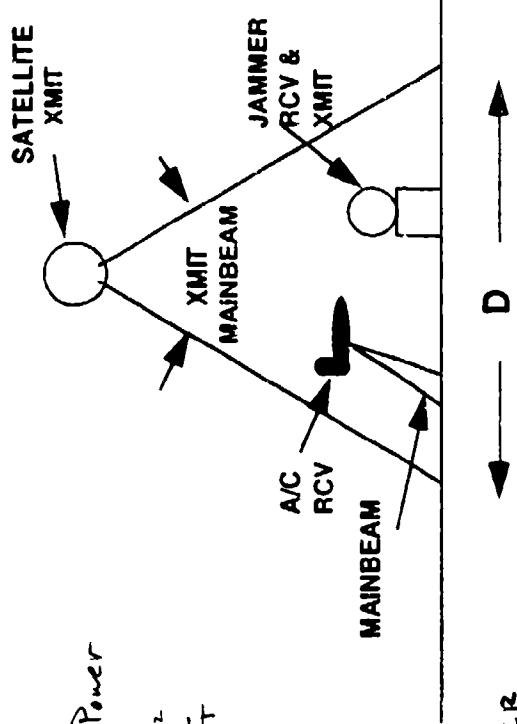
THUS JAMMER CAN DETECT SATELLITE TRANSMITTER TO DETERMINE FREQUENCY AND AND WAVEFORM

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- BISTATIC SAR -
HOWEVER, A/C RECEIVER IS DIFFICULT TO JAM

[REQUIRES HIGH JAMMER POWER]

ASSUME JAMMER

- OPERATES CONTINUOUSLY

- JAMS BANDWIDTH (500 MHZ) EQUAL TO DETECTED BANDWIDTH ABOUT DETECTED CARRIER

- USES OMNI ANTENNA, SINCE RCVR LOCATION IS UNKNOWN

- SAME DISTANCE FROM SAR RCVR AS IMAGED POINT

- NOT IN SAR RCV MAINBEAM

ASSUME SAR

- INTEGRATES FOR T SEC

TO OBTAIN A S/J = 1 REQUIRES A JAMMER AVERAGE POWER

62 KW < JAM AVG PWR < 6.2 MW

$$P_{JAM} = \frac{2 B P_a T \sigma \left(\frac{G_r}{G_{rj}}\right)}{(S_{jj} \tau^2)}$$

G_r = SAR RCV MAINLOBE GAIN $\quad \frac{G_r}{G_{rj}}$ - 50dB

G_{rj} = SAR RCV SIDELOBE GAIN

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